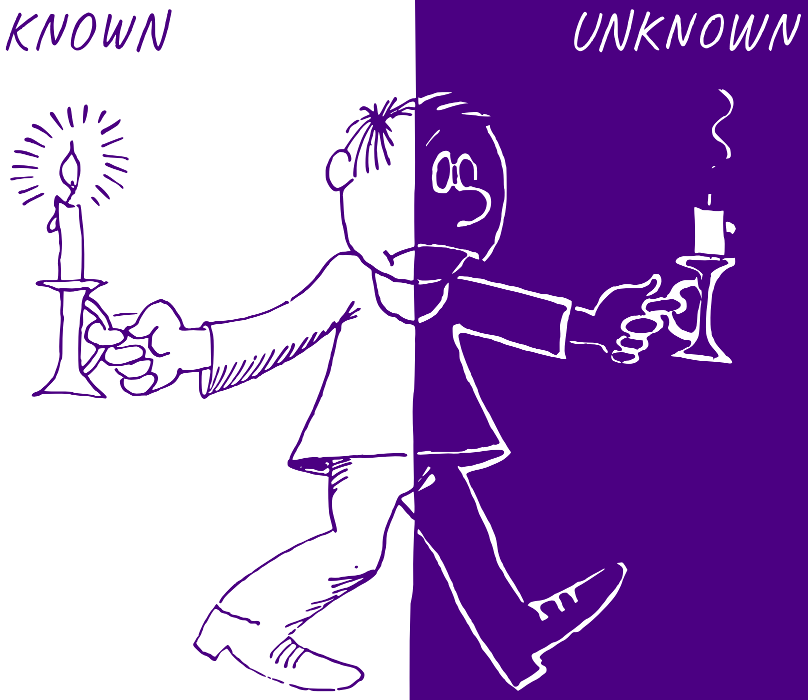
Eureka

Mysteries of the Microworld

Vera Chernogorova



The Mir Titles Project

Eureka

Mysteries of the Microworld

Vera Chernogorova

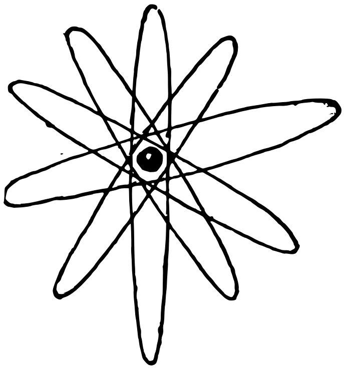
After graduating from the Faculty of Physics and Mathematics, Vera Alexandrovna pursued postgraduate studies and later became a researcher at the Joint Institute for Nuclear Research in Dubna.

For nearly twelve years, she participated in experiments at a particle accelerator, the synchrocyclotron, and co-authored numerous scientific papers on muon research.

In recent years, she has published over ten articles in journals such as Knowledge is Power, Science and Life, and Technology for Youth. Her writings cover topics in nuclear physics, high-energy physics, astrophysics, controlled thermonuclear fusion, scientific advancements in everyday life, and the future of science. Many of these articles have been reprinted in international journals.

Her first book, Mysteries of the Microworld, introduces readers to key issues in particle physics. In 1975, it was awarded a diploma in the All-Union Competition for the Best Popular Science Works.

Mysteries of the Microworld



Vera Chernogorova

Translated from the Russian by
Damitr Mazanav

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V.A. Chernogorova
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Annotation

The world of elementary particles is currently in a state similar to that of chemical elements before D. Mendeleev's discovery of the periodic system. It is a troubling and mysterious situation because it is unclear where elementary particles come from and why there are so many of them. This book by V. Chernogorova explores these questions, discussing what elementary particles have in common and how they differ from one another.

Translator's Note

I discovered this book by accident, while searching for another book. I could not resist the temptation of translating the book for wider audience. This is one of the many books from the phenomenal "*Eureka*" series. I hope to translate several other books from this series. Some books of these series were published by Mir Publishers, but not all. To translate all the books would be a task spanning several years.

I hope that I have done justice to the original work in the translation. Lot of new discoveries have been made in particle physics in last 50 years. Hence where ever I could, I have added footnotes on updated factual information about new discoveries in the field. I have also added a Postface which summarise some of the major achievements and trends in the field. Mistakes and omissions (and I am sure they will be there), if any, are my own.

Damitr Mazanav

Contents

1 The World That Cannot Be Seen

> "Nature rules over things through invisible bodies."
>
> *Lucretius Carus*

The New Leader

Eccentrics make life more colourful. The world would look rather dull without them — these ever-insatiable, terribly restless, extraordinarily inquisitive, and boundlessly curious people. They persistently seek out problems that few understand, struggle with them, and delve into them. They tirelessly discover, invent, and create. The Kazakh poet Olzhas Suleimenov put it well:

> "Every tribe needs at least one person.
> Struck by a star. Find such people."

One does not have to look far to find such a person. Any true scientist is at least a little eccentric. Their thirst for knowledge is unquenchable. Nothing — not war, hunger, destruction, or personal hardship — can stifle a scientist's curiosity, this most precious of human qualities.

In besieged Syracuse, Archimedes solved mathematical problems. In prison dungeons, Kibalchich completed the design of a spacecraft. In starving Petrograd, in blockaded Leningrad, the relentless and unyielding thoughts of researchers continued to live on.

Life presents us with many problems. Some are solved with ease, while others occupy generations of scientists.

Take what seems to be a trivial, almost childlike question: *How is the world structured?* People have been searching for an answer to this for over two thousand years.

A child picks up a toy, and a burning thought strikes them: *What is inside?* Soon, there are broken dolls, shattered spinning tops, and dismantled alarm clocks. One child, finding nothing of interest, discards both the toy and the question along with it. Another, however, holds onto this question for life, transforming curiosity about the toy's inner workings into a quest to understand the inner structure of the world. Such a child is destined to become a scientist.

In the 6th century BCE, this childishly naïve yet philosophically profound question — the question of the world's inner structure — was first asked by an adult.

What is the world made of? This was the question posed by Thales of Miletus, an ancient Greek thinker and one of the founders of science. He, like other scholars of the Ionian school, believed that there must be fundamental material particles, tangible elements from which everything else is composed.

A century later, Thales' follower Democritus took the first steps toward answering this profound question. He proposed that the world consists of two things: invisible, indivisible particles — atoms — and empty space. To Democritus, nature was nothing more than "the chaotic motion of atoms in all directions."

In a beautiful and poetic form, the ancient Roman philosopher — materialist Titus Lucretius Carus presented Democritus' atomic hypothesis. It was through the words of this first populariser of science that the world became

acquainted with one of the greatest hypotheses — the hypothesis of atoms.

For nearly two thousand years, science relied on the speculative hypothesis of Democritus and Lucretius. Only in the 19th century did the English chemist and physicist John Dalton undertake an experimental verification of the atomic views of the ancients.

Experiment followed experiment. With the meticulous precision of a chemist, Dalton carefully weighed the substances involved in reactions and compared the results with the quantities obtained after the reactions.

Dalton's long chemical experiments led to an important conclusion: each chemical substance combines with another only in a *specific* proportion. Just as a kaleidoscope forms countless intricate patterns from the same glass fragments, molecules are composed of the tiniest "pieces" of different substances.

As the saying goes, appetite grows with eating. Dalton sparked chemists' appetite for breaking matter down further. They began to "interrogate" matter in the literal sense — heating, distilling, evaporating, and melting hundreds of chemical compounds. These compounds broke down into separate fragments," distinct pieces" of different types. However, these pieces" remained stable and would not break down any further.

How could these "fragments" of chemical elements not be accepted as the most fundamental particles of mat-

ter, beyond which nothing smaller could exist? How could they not be identified with Democritus' hypothetical atoms?

At this atomic level of matter's structure, the pinnacle of scientific achievement in understanding the world's composition was the creation of the periodic system of chemical elements by D. Mendeleev. He built it based solely on the atomic weights of the elements known at the time and on what Niels Bohr later called his "stunning intuition."

Mendeleev's periodic table has enriched our understanding of the vast diversity of living and non-living forms that exist on our planet. It has played an exceptionally important role in chemistry and physics, stimulating the search for new chemical elements for which empty spaces were deliberately left.

Today, it is used to plan the synthesis of new superheavy elements and to predict the properties of yet-to-be-created synthetic chemical compounds. It serves as the foundation for the entire chemical industry and metallurgy.

However, Mendeleev himself felt a sense of dissatisfaction, as he did not know which natural laws underpinned the periodicity of chemical and physical properties that he had discovered. The fundamental laws of nature — quantum mechanics, which the periodic system of elements ultimately reflects — were only uncovered after scientists began studying matter at the next level, the nuclear level.

> “The insight into the internal causes of phenomena through their external manifestations may be the most important, most valuable, and most fascinating aspect of all science,”

noted Academician Ya. Zeldovich.

Today, the science of matter’s structure has reached such capabilities that it can probe into matter down to 10^{-15} centimetres. Physicists are studying even more “elementary” building blocks of matter than atoms. Why is this important?

Once they succeed in discovering the laws that explain the details of these particles’ behaviour, all their properties, and predict how many of them should exist, we will obtain a “Mendeleev’s table” for elementary particles. This will provide us with the key to understanding a far broader range of phenomena, from the microcosm to cosmology itself.

> “However,” as W. Heisenberg put it, “a unified theory of the micro- and macro-worlds remains, to a large extent, ‘the music of the future’ to this day.”

But perhaps the composer who will be able to write it is already growing up…

Now, let us return once again to those distant times when atomism was experiencing its triumph.

Chemistry not only introduced us to atoms but also provided them with a special label. A label affixed to a product loudly proclaims its quality and includes instructions for

its use. The chemical label on atoms declared their indivisibility and unchangeability as their fundamental properties.

The chemists' categorical judgment at that time led to a corresponding dismissive attitude toward atoms. Indeed, if atoms were truly indivisible, then why waste time trying to understand their structure?

Newton wrote:

> "It seems to me that God, at the very beginning, created matter in the form of solid, impenetrable, movable particles and that He endowed these particles with such sizes, shapes, and other properties, and created them in such relative quantities, as were necessary for the purpose for which He formed them."

All the evidence gathered by that time pointed to only one conclusion: *the impossibility of chemically affecting atoms*.

But why only chemical effects? Where were the physicists? At that time, physicists were not interested in atomism. Not because atomism did not deserve their attention, but simply because physicists were almost powerless then. They looked at atoms through the eyes of chemists, trusting them implicitly.

Physicists were almost powerless. But then, in their modest arsenal, they found one instrument...

A Familiar Stranger

Physicists were fortunate. They did not need to invent and patent a new device. They did not have to build a complex and expensive installation like a modern accelerator. Everything turned out to be much simpler.

A fragile glass tube, several dozen centimetres long, with electrodes embedded in it, had faithfully served generations of physicists. It was used to study electrical discharges in gases at low pressure.

This was the discharge tube — the most popular instrument of the 19th century. It was this device that became the tool through which the first notes of atomic and nuclear physics were played.

Physicists calmly and methodically studied electrical discharges in gases. They carefully recorded facts and figures in their notebooks, characterising what seemed to them an entirely familiar phenomenon.

If only they had known! But no one even suspected that the substance inside the tube was not at all like the matter we encounter in everyday life. No one realised that, under the influence of the applied voltage, the tube contained a substance in a completely new, yet unknown state — matter broken down into negatively and positively charged particles. Matter in a new, fourth state!

Inside the ordinary, well-known discharge tube was *plasma* — the very plasma without which modern physics

would be unimaginable.

Inside the ordinary, well-known discharge tube was plasma — the very plasma without which modern physics would be unimaginable.

But the paths of science are unpredictable, as everyone now knows. As early as the mid-19th century, the English physicist and chemist William Crookes discovered that a stream of negatively charged particles flowed from the cathode to the anode in a discharge tube. Physicists received this news with indifference. But Crookes himself drew an extraordinary conclusion from it.

> "We have already," he wrote, "as if grasped the indivisible particles that obey our control, which can reasonably be assumed to be the physical foundation of the universe."

It took science thirty long years to confirm that, under the influence of voltage, a stream of fragments of "indivisible" atoms was indeed rushing through the gas discharge tube!

Professor Joseph John Thomson of the Cavendish Laboratory, whom his friends simply called "J.J.," began a detailed study of cathode rays.

It all started with a physicist's natural curiosity to understand the nature of the unknown particles discovered in the tube. A brilliant experimenter, J.J. Thomson conducted a series of precise and ingenious experiments. He discovered that cathode rays were a stream of electrons

— carriers of elementary negative charges. Later, he measured the *charge-to-mass* ratio and, finally, the *mass* of the electron.

In a new series of experiments, J.J. Thomson sought to determine whether the properties of electrons depended on the type of gas in the discharge tube.

The answer took him by surprise. All electrons turned out to be *completely identical*. So, apart from atoms, were there other, even smaller particles? Did these particles exist in all atoms of all elements? And were atoms, once thought to be indivisible for all eternity, not so simple after all?

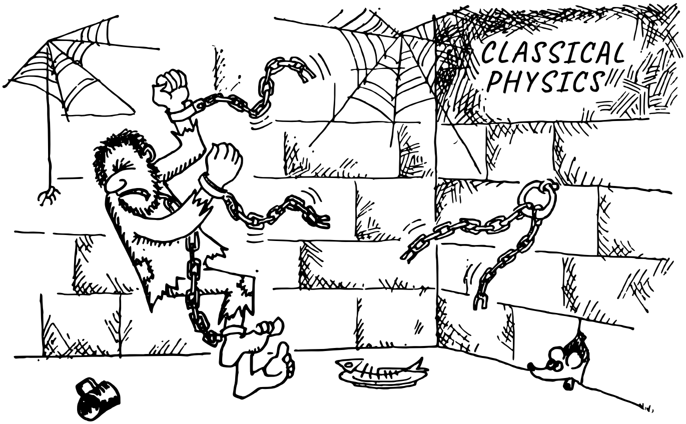
Calm and balanced by nature, J.J. Thomson was, in both intellect and temperament, the least likely candidate to be a revolutionary in science. He not only lacked the temperament of a radical who overturns fundamental principles but also never sought to challenge them.

Innovation is the domain of the young. For a forty-year-old professor at the Cavendish Laboratory, it was more natural to consolidate established positions rather than challenge them. Thomson was educated in the finest traditions of classical physics. He never doubted its universality and power.

And then, everything collapsed. What was to be done? Should he continue to revere the label of chemical atomism? Or should he acknowledge the existence of particles even more fundamental than the so-called "indivisible"

atom?

To J.J. Thomson's credit, the inner struggle between the innovator and the conservative ended in victory for the innovator. The experimental physicist — who saw facts as the most real, if not the only real, thing on Earth — prevailed over the man bound hand and foot by the dogmas of classical physics.



Two Contenders

The discovery of the electron, for which J. J. Thomson was awarded the Nobel Prize, still did not answer the fundamental question: *What is the structure of the atom?* The mystery remained unsolved.

But let us not be unfair to the era of our grandparents... For at the very end of the last century, physicists finally

obtained the tool that, in our own time, has allowed us to probe deep into the atom.

It all began at the University of New Zealand, where a young student, Ernest Rutherford, the future father of nuclear physics, sat in class. This student dared to question the prevailing chemical views on the atom. As proof, he titled his first scientific work *The Evolution of Elements*.[1]

[1] The full title of the work is *The Constitution Of Matter And The Evolution Of The Elements* and was published with other articles in Popular Science Monthly, August 1915. Can be accessed here. – DM

After graduating in 1894, Rutherford traveled to England for further research. He was fortunate — he joined J.J. Thomson's Cavendish Laboratory.

At that time, an event took place that the author of *The Evolution of Elements* could not ignore. In 1896, Antoine Henri Becquerel, a member of the distinguished family of French physicists, discovered *radioactivity*. In other words, he observed the spontaneous decay of atoms. This discovery dealt a final blow to the idea that atoms were the smallest, indivisible particles of matter.

Together with Thomson, Rutherford began investigating the nature of this newly discovered radiation. Before long, he uncovered a highly promising feature. Rutherford successfully demonstrated that radioactive emissions were not uniform but consisted of at least two distinct components: light beta particles — easily recognizable as Thomson's electrons — and heavy, positively charged alpha particles.

The golden days of Rutherford's collaboration with Thomson ended quickly. He moved first to Canada and later to

Manchester. But he did not leave the Cavendish Laboratory empty-handed. In a figurative sense, he carried a loaded gun in his back pocket. And once a gun is created, it is bound to fire — sooner or later.

Rutherford's gun fired late. By then, he was over forty, a respected professor at the University of Manchester, a renowned expert in radioactivity, and a Nobel laureate.

Rutherford fired heavy alpha particles at atoms. Between the source of the alpha particles and a photographic plate, he placed thin films of different materials. In this setup, the black spot on the developed plate — the mark left by alpha particles — had blurred edges. The atoms in the films slightly altered the trajectory of the alpha particles.

Rutherford was shooting at atoms. But his alpha projectiles were not meant to destroy them; they were meant to *probe* them.

His initial shots were unsuccessful. The fast-moving alpha particles passed almost unhindered through the thinnest films, barely deviating from their straight paths. This seemed to confirm the old idea put forward by Thomson — that *an atom was a positively charged sphere uniformly filled with electrons*.

Yet something about Thomson's atomic model did not sit well with Rutherford. And this lingering doubt drove him to continue his research.

Rutherford assigned his student, Marsden, the task of shooting alpha particles. He instructed him with the words:

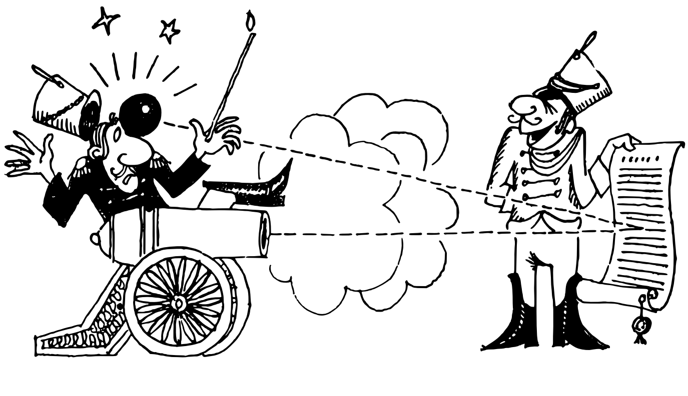
"I do not expect anything interesting from your experiments, but observe nonetheless."

"Observe" — a quintessential Rutherford word! It was filled with optimism. "Observe, just in case something new appears." For Rutherford, science was a constantly growing tree, one that the gardener himself had to shape. He believed in always being ready to cut off dead branches to allow new shoots to grow.

New shoots appeared very soon. Marsden discovered that some alpha particles, after penetrating a thin layer of material, deflected by 90°, and sometimes even by 180° degrees!

Rutherford later wrote:

> "This event seemed about as probable as if you had fired a 15-inch shell at a piece of tissue paper and the shell bounced back and hit you."



What had happened? The answer was obvious: the alpha particles were colliding with a massive charged body, far heavier than an electron or even the alpha particle itself.

The first explorers sent into the depths of matter brought back astonishing news — a nucleus lay at the centre of the nearly empty atom. It was positively charged and a hundred thousand times smaller than the atom itself. Behind its powerful electric barrier, like treasures hidden behind towering fortress walls, the secrets of the atom were securely locked away. But what were they? Could there be unknown particles carrying a positive electric charge?

Physicists are passionate people. The moment they discover something new, they throw themselves at it with full force.

The atomic nucleus! From that moment on, Rutherford's entire focus shifted to it. How could one get closer to the nucleus? How could one overcome its electric barrier? Today, this is easy to do — one only needs to accelerate a proton to just one mega-electron-volt[2] of energy.

But Rutherford had no accelerator!

Rutherford thought, his colleagues thought, his students thought. The solution was first found by the grandson of the great Charles Darwin, who was working with Rutherford at the time. He suggested starting with the nuclei of the lightest elements — since they had a lower charge and, therefore, much weaker defences.

The lightest element in the universe is hydrogen. There-

[2] An electron volt (eV) is a unit of energy equal to the amount of kinetic energy gained by an electron when accelerated through a potential difference of one volt. One mega-electron-volt (MeV) is equal to one million electron volts. – DM

fore, a special chamber was filled with hydrogen and bombarded with alpha particles. The experiments were conducted by the same Marsden.

But what does "conducted" mean? Today, physicists have a wide range of recording equipment at their disposal. It detects, records, logs, visualises data as graphs, and even systematically organises experimental results.

Back then, things were different. Marsden spent hours sitting in front of the chamber. Bright flashes appeared on the screen one after another. These were not alpha particles — they simply could not have reached the screen. This meant that in the chamber, alpha particles were transferring their energy to the light hydrogen nuclei, whose flashes appeared on the screen.

Marsden then evacuated the hydrogen from the chamber and, as a control, filled it with nitrogen. Yet the flashes continued to appear — was this an error? How could hydrogen nuclei appear in a nitrogen-filled chamber? Was the chamber not properly cleaned? Or was something else happening? It had to be verified.

World War I shattered all plans. Within days, the laboratory was empty. Marsden fought in the British army, while his friend and Rutherford's close collaborator, Hans Geiger, fought on the German side. Henry Moseley, Rutherford's favourite student, was killed on the front lines.

Rutherford, along with several lab assistants, abandoned scientific research to work on developing a device for de-

tecting submarines.

Yet his thoughts kept returning to the unusual results Marsden had obtained just before the war. What if the chamber had been completely evacuated? What if Marsden had not been counting hydrogen nuclei on the screen? But then what was he seeing?

Both excited and apprehensive about this idea, Rutherford secretly re-examined his student's experiments at night. He evacuated the chamber repeatedly until there should not have been a single hydrogen atom left. Yet as soon as he refilled it with nitrogen, the flashes reappeared on the screen.

How he missed his European colleagues in those moments! How the war hindered him! It had not only divided scientists but had also slowed down science itself.

At the end of 1916, Rutherford wrote to his friend, the Danish physicist Niels Bohr:

> "I detect and count light atoms set in motion by alpha particles, and these results shed bright light on the nature and distribution of forces near the nucleus. I am attempting to break open the atom using the same method."

And most importantly:

> "I have obtained some results that seem quite astonishing, but it will take heavy and prolonged work to provide solid proof of my conclusions."

What were these “some results”? Nothing less than the world’s first nuclear reaction! The first artificial splitting of a nitrogen nucleus by an alpha particle, accompanied by the emission of a lighter hydrogen nucleus.

The researcher alternately filled the chamber with nitrogen, air, and pure oxygen. In all three cases, the screen showed the presence of hydrogen nuclei. However, the list of investigated elements soon reached a limit — heavier nuclei were inaccessible to low-energy alpha particles.

For Rutherford, however, the results were more than sufficient. He no longer doubted that he had discovered the very same positively charged “component” present in all atomic nuclei.

This conclusion was further confirmed by other scientists who were also searching for the lightest positively charged particle using discharge tubes. There, in the opposite direction — from anode to cathode — flowed a stream of gas ions, meaning atoms stripped of their electrons. The lightest particle among them was the nucleus of a hydrogen atom, having lost its single electron.

Thus, the second elementary particle — the proton, the nucleus of the hydrogen atom — was born.

The proton is 2,000 times heavier than the electron. It perfectly matched scientists’ expectations of a possible carrier of positive charge in the atom, aligning well with the large mass of the atomic nucleus.

Unlike the electron, whose discovery sparked fierce

scientific debates and challenged established ideas, the proton's discovery faced no such resistance. One could say that all the struggle and controversy of scientific battles had already been borne by the electron.

And so, physicists now had two fundamental "building blocks" of matter. They seemed quite satisfied:

> *all substances were composed of atoms, and atoms, in turn, were made of electrons and nuclei.*

The Third, But Not the Last

A small piece of radioactive material lay near a beryllium plate. Alpha particles passed through the beryllium, knocking out protons. The Geiger counter, replacing the easily fatigued and error-prone eye of the experimenter, clicked as it counted the number of particles emerging from the foil.

It was an ordinary working day in one of Germany's physics laboratories in the early 1930s. Professor Walter Bothe and his colleague Becker were organising their notes.

When the proton count was completed, they moved the Geiger counter away just enough so that the protons emerging from the beryllium would not reach it. They then reapplied high voltage to measure the background counts.

Yet, the Geiger counter continued to register activity. They moved it even further away — still, it kept clicking. Surprise turned to confusion. What could the counter be

detecting at such a great distance?

Could it be gamma rays — electromagnetic radiation more penetrating than protons? A lead plate should have blocked them effectively. But even a lead shield did not help; the clicks continued at the same rate. A second and third lead plate were also powerless to stop them.

A wave of some unusual radiation was reaching the Geiger counter, for which a thick layer of lead was no more of an obstacle than a sheet of cigarette paper. Yet, Bothe and Becker failed to take the decisive step and exclaim, "These must be new, unknown particles, gentlemen, knocked out from beryllium nuclei!" Instead, they quietly recorded in their laboratory journal: "Ordinary gamma quanta of high energy detected."

In France, the "beryllium" radiation caught the interest of Irène and Frédéric Joliot-Curie. However, the French physicists merely repeated the conclusion of their German colleagues. "Exceptionally penetrating gamma rays," they declared — despite the fact that this conclusion violated a fundamental law of mechanics, the law of conservation of momentum.

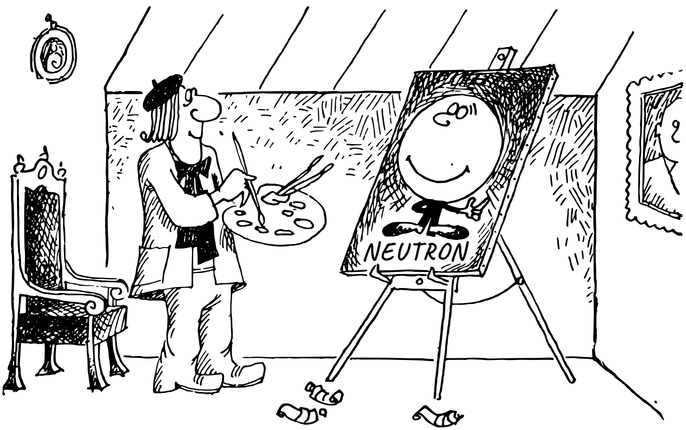
It was Rutherford's student, a member of the Royal Society of London and future Nobel laureate, James Chadwick, who finally identified the elusive particle that had twice eluded recognition.

In February 1932, a month after the Joliot-Curies' report on the "exceptionally penetrating gamma rays," a short let-

ter to the editor appeared in the British scientific journal *Nature*, signed by James Chadwick.

> "These experimental results," wrote the author, "are very difficult to explain based on the hypothesis that beryllium radiation consists of electromagnetic waves, but they follow directly from the assumption that the radiation consists of particles with a mass equal to that of a proton but without charge."

James Chadwick had provided an almost exact "portrait" of a neutral elementary particle — the *neutron*. Since the neutron carried no electric charge, it had remained so elusive.



The heavy neutral particle — the neutron — was warmly welcomed by physicists. Its discovery resolved the tricky question of nuclear stability. With the presence of neutrons, which could reliably counteract electrostatic repul-

sion, electrons were permanently expelled from the nucleus.

The list of elementary atomic particles was now complete. Atomic nuclei of all chemical elements were composed of heavy protons and neutrons (which came to be called nucleons), while electron shells determined their chemical behaviour.

A New Role

A child assembling a picture from colourful beads places them into special slots. An artist creating a mosaic binds its individual pieces together with cement.

A physicist, however, builds their picture of the world by arranging atoms and atomic nuclei from various combinations of elementary particles. But what kind of picture can be considered complete if its individual components are not bound together? Where is the cement, the glue that holds protons and neutrons within nuclei? *What forces keep them together?*

Could it be the familiar force of gravity? No, gravitational attraction is too weak to hold protons and neutrons together — their masses are too small. Electromagnetic forces do not fit either: like-charged protons would simply fly apart. And what, in that case, would hold the neutrons?

After discovering the atomic nucleus, Rutherford was determined to uncover the mystery of the forces acting

within his newly discovered microscopic object. He carefully observed how alpha particles interacted with nuclei.

> "If these forces had not been detected before," Rutherford reasoned, "then they must only appear at very small distances. But how close must one be to feel their influence?"

Experiment followed experiment. Years passed, yet there was still no definitive answer. Even when atomic probes approached heavy nuclei as closely as 10^{-12} cm, nothing extraordinary was observed — only the familiar electrostatic repulsion, just like that seen in school demonstrations of Coulomb's law with like-charged spheres.

And then — great excitement! Alpha particles, coming ten times closer (to a distance of 10^{-13} cm) to hydrogen nuclei — protons — encountered an unusual interaction. This was no longer electrostatic in nature. It behaved in an entirely different way. The space within 10^{-13} cm was under the control of *nuclear forces*.

In the remarkable year of 1924, Rutherford and his colleagues succeeded in splitting the nuclei of nearly all light elements. In every case, they observed the emergence of protons with energy significantly greater than that transferred to them by alpha particles.

But why greater? Could the law of conservation of energy be violated?

Not at all. This was simply a result of nuclear forces at work. The protons gained additional momentum from the

internal energy reserves of the nucleus — the very nuclear energy that we now harness in atomic power plants.

Thus, the "cement" by which nature assembles the mosaic of different substances was discovered.

Nuclear forces are a *thousand times* stronger than electromagnetic forces. They effortlessly bind together a single proton and neutron in the hydrogen isotope deuterium, as well as hundreds of protons and neutrons in heavy nuclei like those of uranium.

So, physicists discovered new forces in nature and gave them a name. But that does not mean they immediately understood their true nature or fully uncovered their underlying mechanisms. These newly discovered forces were called "nuclear." But can one deduce everything about a person just from the surname Ivanov?

Still, when encountering an unfamiliar Ivanov, at least you are certain he is a human. In contrast, the physical foundation of nuclear forces remains unknown to this day. Since Rutherford's time, more human hours have been spent studying nuclear forces than on any other scientific question in human history. Scientists have determined many of their properties, yet a rigorous theory of nuclear forces has yet to be developed.

Physicists are still unable to express in precise mathematical form this extraordinary attraction between protons and neutrons. In this case, even the all-powerful mathematics remains powerless.

Could it be possible to at least imagine the mechanism of nuclear forces? But how can one attempt to describe a new phenomenon in the microcosm when there is neither a theory nor experimental results?

When studying the macroscopic world, physicists often rely on analogies. But is this method applicable to nuclear processes?

Analogy is based on the principle of the material unity of the world. No matter how astonishing elementary particles may be, they are all material in nature. They all possess properties characteristic of macroscopic objects, such as motion, energy, and so on.

Using the method of analogy, Academician I. Tamm and Professor D. Ivanenko suggested as early as 1934 that nuclear interactions might be mediated by the electron and neutrino, which are emitted during beta decay[3] of nuclei. This would be somewhat similar to how charged bodies interact with each other by exchanging particles of electromagnetic radiation — *photons*.

A twenty-eight-year-old theorist, Hideki Yukawa, a lecturer at Osaka University, took up this idea and made a bold new step. A year later, he proposed a new role for an as-yet-undiscovered elementary particle — a *carrier* of nuclear forces. Carefully describing the properties that this candidate for the vacant position should possess, the Japanese theorist suggested that experimentalists look for it in *cosmic rays*[4].

[3] Beta decay is a process where a neutron in an atom's nucleus turns into a proton, releasing an electron and a tiny particle called a neutrino. This changes the element because the number of protons in the nucleus increases by one. It's one way unstable atoms become more stable. – DM

[4] Cosmic rays are high-energy particles, mostly protons and atomic nuclei, that travel through space at nearly the speed of light. They originate from the Sun, distant supernovas, and other cosmic events. When these particles collide with Earth's atmosphere, they create showers of secondary particles, which scientists study to learn about the universe and the nature of matter. – DM

Until then, physicists had always first discovered a new elementary particle and only then found its place in the general picture of matter's structure. Now, for the first time, experimenters began their work with a precise theoretical assignment.

At that time, scientists had become seriously interested in cosmic radiation, which originates in the upper layers of the Earth's atmosphere. They were studying the mechanism of interaction between cosmic rays and atmospheric matter, attempting to measure their energy using a Wilson chamber.

The Wilson chamber is an interesting, simple, and useful device. In it, supersaturated vapour cools and condenses into tiny droplets, forming around the ions left behind by a charged particle passing through the chamber. Created in 1911 by C. Wilson, this device quickly gained popularity and became the "supreme court of physics." Indeed, earlier, scientists could only observe the behaviour of large masses of particles. The Wilson chamber made it possible to visualise and photograph the traces of individual inhabitants of the microcosm.

Experimentalists cast their "net" — the Wilson chamber — into cosmic rays, and a year later, they "caught" an unknown particle. It closely resembled the one Yukawa had described. Its mass was precisely intermediate between that of a proton and an electron. Because of this, it was named the *meson*, from the Greek word *mesos*, meaning "middle."

Physicists rejoiced, but their joy was short-lived. Upon closer examination of the new particle, they were astonished. The mu-meson, as the newly discovered particle was called, turned out to be an extremely penetrating component of cosmic radiation. It interacted very weakly with nucleons, making it entirely unsuitable for the role of Yukawa's particle.

Such is the nature of physics — much like life itself. You search for one thing but discover something entirely different. But what purpose do these mu-mesons serve? What is their "specialty"? Where should one place this meson brick, generously gifted by nature?

The situation physicists found themselves in resembled the predicament of Krylov's curious little monkey[5], who had gotten hold of a pair of glasses but had no idea what to do with them.

For nearly four decades, physicists have been trying to

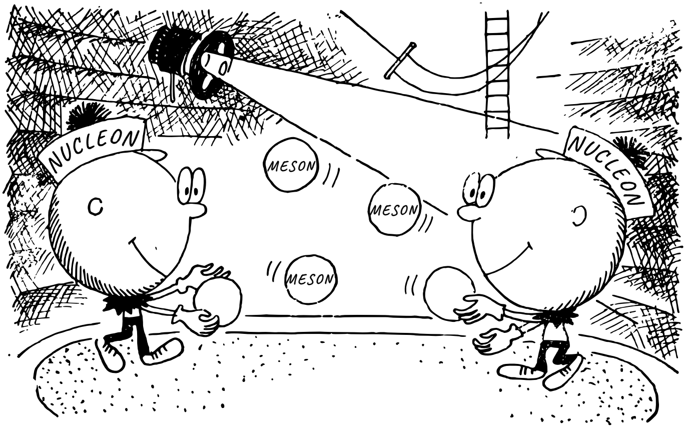
[5] This refers to a famous fable by the Russian writer Ivan Krylov, *The Monkey and the Glasses.* In the story, a monkey finds a pair of glasses but doesn't know how to use them. No matter how it twists or turns them, the glasses don't seem to help. Frustrated, the monkey smashes them, failing to realize their true purpose. – DM

uncover the special role of the mu-meson, but all their efforts have been in vain. The life of this particle has been studied down to the finest details. A new scientific field with practical applications, mesochemistry, has even emerged. But how cunning this mu-meson is! What is it? No one knows. It is only known that, in the microworld, it behaves merely as a 200-times-heavier version of the electron. The mystery of the mu-meson remains unsolved.

Twelve years passed. Then, one day, in collisions of fast protons with atomic nuclei, another particle was discovered. Heavier than the previous one, it possessed all the characteristics that allowed it to be considered a candidate for Yukawa's particle. Unlike the mu-meson, which was indifferent to nucleons, this new particle interacted strongly with atomic nuclei.

Physicists were overjoyed. The newly discovered particle, named the pi-meson, perfectly matched the theoretical description of a nuclear force carrier. By constantly exchanging mesons, nucleons in the nucleus remain bound together, much like circus jugglers who toss multiple objects back and forth. However, while circus performers juggle stable props, nucleons exchange mesons that are instantly emitted and absorbed. Neutrons and protons exchange mesons with positive and negative charges, while protons with protons and neutrons with neutrons exchange neutral mesons...

In 1947, this discovery culminated in Hideki Yukawa being awarded the Nobel Prize.

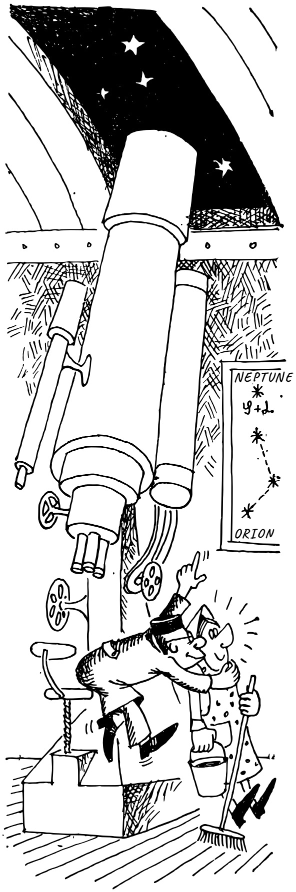


By 1950, the world was thought to be composed of protons, neutrons, electrons, mu-mesons, pi-mesons, and photons. Scientists understood how these building blocks formed the vast pyramid of the macroscopic world and why any piece of matter did not simply fall apart into elementary particles.

There was only one question left unanswered — *where did the mu-meson brick fit?*

Under the Invisible Cloak

On one of the last nights of 1846, the German astronomer Johann Galle discovered a new planet at the exact location predicted by the mathematician Urbain Le Verrier. It was named Neptune. This was a triumph of classical physics.



> "In our time," wrote the American scientist Philip Morrison in 1956, "physics is awaiting another such discovery. There is its own 'Neptune' among the elementary particles — an extraordinary particle mentioned in every physics review, though it has yet to be found."

And then, some physicists began to entertain a heretical thought: could it be that in certain nuclear processes, the law of energy conservation *does not* hold? The idea was so sacrilegious that they tried to dismiss it, to forget about it.

Scientists were bewildered. Only one of them, the Swiss physicist Wolfgang Pauli, found a clever way out of this dilemma, thus eliminating the threat looming over the law of energy conservation.

In December 1930, he sent a letter to a scientific seminar in Tübingen, concluding with the words:

> "...without risk, there is no gain; therefore, every possible path to salvation must be seriously considered. So, my dear radioactive ladies and gentlemen, examine and judge."

Pauli proposed that there existed another, yet undiscovered particle that was emitted alongside the electron during nuclear beta decay. The energy, he suggested, was not simply divided between the nucleus and the electron, but also shared with this unknown particle — just as the energy of gunpowder is randomly distributed among the pellets fired from a shotgun.

And suddenly, everything fell into place. If the electron was emitted with less energy than expected, the missing energy was carried away by the mysterious, unseen particle.

Pauli's hypothesis was not immediately accepted by all. Physicists debated fiercely. On one hand, it was difficult to abandon the fundamental law of energy conservation. On the other, they were now forced to introduce yet another, and an exceedingly unusual, particle into an atom that had seemed fully accounted for.

Consider this: all other particles could be detected — by Geiger counters, by the traces they left in Wilson's cloud chamber. Neutrons and gamma quanta revealed their presence by colliding with protons or knocking electrons out of atoms.

But the mysterious particle stubbornly eluded experimenters. Meanwhile, Pauli, as if teasing them, had already prepared its "identification card," listing its key characteristics: light, with a mass close to zero, and electrically neutral.

Why, these are the "passport details" of the *neutrino*! Its name, translated from Italian, means "something small and neutral."

A neutron, when passing through dense matter, can travel several metres without hitting a single nucleus. Impressive? Certainly. But not when compared to the neutrino. This elusive particle can fly through dense material for billions of years at the speed of light before its first

collision.

Its incredible penetrating ability is the neutrino's greatest mystery.

In life, we encounter two types of interaction. One is gravitational attraction, which we experience from early childhood — rubbing bruised knees and foreheads from falls. But gravity does not just throw us to the ground; it also keeps us there. It holds the Moon around the Earth and the planets around the Sun.

The other type, known as the *strong interaction*, was demonstrated earlier through nuclear forces that bind protons and neutrons within the atomic nucleus. At short distances, these forces are a thousand times stronger than electromagnetic forces.

But the neutrino revealed to us a new type of interaction — the *weak interaction*. Other elementary particles can interact in multiple ways, but nature deprived the neutrino of such choices. Its fate is to engage in only one kind of interaction — the weak one.

And it is very weak — hundreds of billions of times weaker than the electromagnetic force. This made the neutrino extraordinarily "unsociable." For a quarter of a century, experimenters failed to detect this elusive particle. The neutrino slipped through their instruments like a tiny fish passing through a net with wide mesh.

Yet, as scientists deepened their understanding of weak interactions, the importance of the neutrino grew. It be-

came clear that neutrinos are produced during nuclear reactions on the Sun and in distant stars. Neutrinos are everywhere. Every square centimetre of the Earth is penetrated by billions of neutrinos every second. Truly, we live in an endless ocean of neutrinos.

Shortly before the discovery of the neutrino, one of the experiment's participants gave his colleagues a New Year's gift. Under the festive wrapping was a painted matchbox with an inscription: "Guaranteed to contain at least 100 neutrinos."

Physicists were able to detect the tiny invisible particle only after creating nuclear reactors — powerful sources of neutrinos. Out of every 10^{20} neutrinos passing through the detector, only a single one would be captured. However, the neutrino flux was so immense that even this minuscule fraction was enough for its detection.

Thus, in 1956, F. Reines and C. Cowan from the Los

Alamos Laboratory dispelled the mysterious aura surrounding the neutrino.

Extraordinary Bricks

It is always the same: if a gardener rejoices at the rain, a tourist curses the untimely downpour. The sun shines brightly — someone benefits, while another suffers. Alas, perfection does not exist, and it is impossible to please everyone.

Before the discovery of the neutron, physicists believed that the atomic nucleus consisted of protons and electrons. This greatly troubled theorists — their calculations did not add up. However, experimentalists studying radioactive beta decay were completely unbothered; they did not have to puzzle over where electrons came from.

The discovery of the neutron turned everything upside down. Now, theorists rejoiced because the neutron-proton model of the nucleus resolved all their difficulties. But their joy faded when they glanced at those studying radioactivity. These researchers demanded an answer to one difficult but crucial question: *where do the electrons in beta decay come from if they are not present in the nucleus?*

Did this mean abandoning such a beautifully simple model of the nucleus and taking a step backward? After finally glimpsing clear horizons, must physicists once again plunge into the daunting abyss of contradictory and

incomprehensible facts?

The direct question — *where do electrons in the nucleus come from?* — forced physicists to take a giant leap forward, perhaps as significant as recognising the existence of electrons in the first place.

Twenty-three centuries ago, Democritus endowed atoms with the property of indivisibility and immutability. At the very end of the 19th century, physicists tore that label off atoms and, without hesitation, reassigned it to elementary particles! It was difficult for them to imagine the building blocks of matter without their familiar, reassuring label.

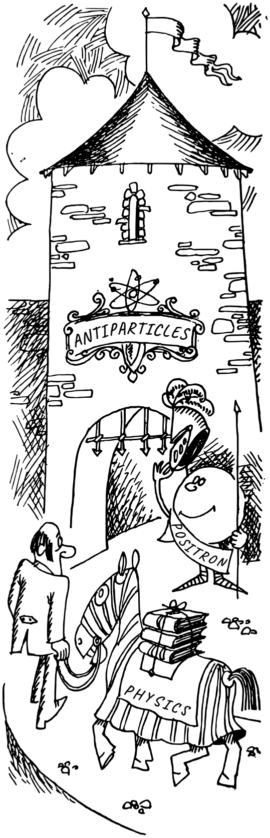
Werner Heisenberg, the founder of quantum mechanics, was the first to solve the mystery of the nucleus. He proposed that a neutron in the nucleus could sometimes transform into a proton, an electron, and a neutrino. The proton remained in the nucleus, while the other two newly formed particles escaped. This transformation outwardly appeared as radioactive beta decay.

So that is where electrons come from! For the first time, researchers of the microscopic world had discovered the mutual convertibility of elementary particles.

Later, it was found that outside the nucleus, a neutron survives for no more than 12 minutes before decaying into a proton, an electron, and a neutrino. Nothing similar happens to a free proton. However, within a radioactive nucleus, the energy conditions can be such that even a stable proton can transform into a neutron, a positron, and

a neutrino. This event, named after the elementary particle *positron*, became known as *positron decay*.

What is this new particle — the *positron*?



It is both new and seemingly familiar. It is an exact copy of the electron, only with the opposite electric charge. At first glance, it might not even be worth mentioning if it were needed only to explain a few words about positron decay in nuclei.

But that is not the case. This particle plays a special role in the history of elementary particle physics. The discovery of the positron opened the door to the world of antiparticles. It revealed yet another property of matter — its ability to transform from a tangible form into energy!

It all began in 1931 when a young theoretical physicist from Cambridge University, Paul Dirac, derived an equation describing the motion of an electron. Soon, he discovered that this equation had two solutions, meaning that, in addition to the electron, it could also describe another particle. This particle appeared to be completely analogous to the electron but carried a positive electric charge.

At that time — more than forty years ago — no one had heard of *anti-particles*, and the only positively charged particle known to physicists was the proton. However, due to its large mass, the proton did not fit the second solution of Dirac's equation.

At first, it seemed like a purely mathematical oddity. But all attempts to eliminate the second solution led nowhere.

There were only two possibilities: either Dirac's theory was incorrect, or a positively charged electron existed in nature.

Dirac's prediction was so extraordinary that even the greatest scientists were slow to accept it. For example, when Dirac gave a lecture on antiparticles in Kharkiv, Landau repeatedly muttered, "Dirac is a fool, Dirac is a fool." Yet, three decades later, he declared, "Who can argue that Dirac accomplished more for science in a few years than everyone in this room has in their entire lives?"

A year later, in 1932, the positron was discovered in cosmic rays. In a Wilson chamber, researchers found traces of particles that could only belong to an electron — but with a positive charge.

When studying cosmic rays using the Wilson chamber, experimenters employed a method first proposed in 1927 by Soviet physicist D. Skobeltsyn. The Wilson chamber was placed between the poles of an electromagnet. This setup not only allowed them to observe the tracks of elementary particles but also to measure their energy and determine the sign of their electric charge based on the curvature of their paths in the magnetic field. In the photographs taken in the Wilson chamber, it was clearly visible that the tracks of electrons and positrons curved in opposite directions.

The experiment confirmed the theory. Twenty-eight-year-old Paul Dirac joined the ranks of Nobel Prize laureates.

After the discovery of the positron, a new question arose: does every elementary particle have an “anti-reflection”? Experimenters began searching for the anti-proton in cosmic rays. The electron-positron pair seemed to confirm Dirac’s theory. But now and then, doubts crept in — what if nature had made an exception for these particular particles?

> “The time gap between the prediction of the antiproton and its observation in 1955 was too long,” said Academician Ya. Zeldovich, “and some theorists lost their nerve — in the last few years, attempts were even made to build a theory without antiprotons.”

Only a quarter-century after Dirac’s prediction, a team of American scientists led by Emilio Segrè and Owen Chamberlain discovered the anti-proton. A year later, the anti-neutron was found.

Grasping the positron thread, physicists began pulling in the net of anti-particles — first slowly, then faster and faster. Now, no one doubts that every elementary particle has its own shadow — a corresponding antiparticle.

While studying positron tracks in the Wilson chamber, physicists immediately noticed that when an electron and a positron meet, they annihilate each other.

There was no reason to fear for nature — nothing was lost in the process. The mass of both particles transformed into another form of matter — energy, the amount of which could be easily calculated using Albert Einstein’s famous

formula: $E = mc^2$.

> "This result of modern physics," wrote Nobel laureate Max Laue, "is the most astonishing of all that the progress of natural science has ever brought."

How strange the fundamental building blocks of matter turned out to be! Even such stable particles as the proton and electron could "disappear" when meeting their corresponding anti-particles. One could not help but wonder — how have ancient rocks, composed of such seemingly fragile material, managed to survive to this day?

The key lies in the fact that elementary particles are willing to undergo transformations only under specific conditions — within radioactive nuclei or upon encountering their anti-particles. In the accessible part of our world, stable nuclei vastly outnumber radioactive ones. And what saves us from annihilation is the absence of significant quantities of anti-particles.

The Era of Hyperons

Not long ago, physicists were sometimes hesitant to accept the new particles that nature presented to them. However, by the early 1950s, their mindset had changed significantly. Growing bolder, they began "inventing" new roles for yet-to-be-discovered fundamental building blocks and then searching for the particles that could play these roles. Like the seafarers of Columbus' time, physicists ventured into the alluring, uncharted realm of the microcosm, driven by

the quest for new particles.

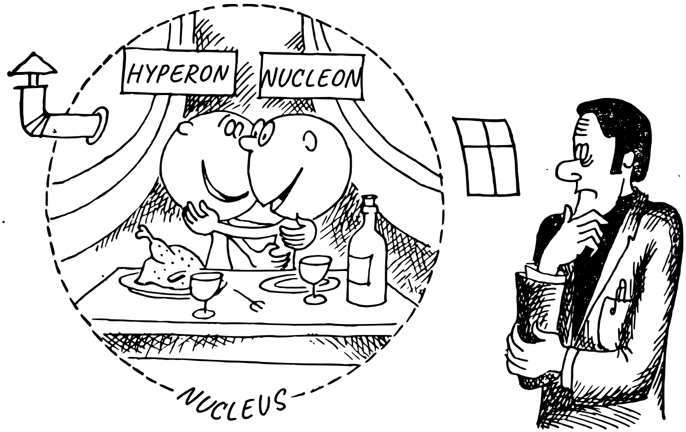
Using Wilson chambers, scientists studied collisions of elementary particles with nuclei. They placed plates made of specific materials inside the chamber, tracking both the path of an incoming particle and the traces of those that emerged from the plate.

Then, in 1951, a remarkably "strange" particle took the "bait" — a lead plate. High-energy cosmic rays, colliding with the protons and neutrons of the lead plate, produced a new neutral particle. This particle itself left no trace, but nearby, two charged particles were seen scattering from a single point, marking the decay of the invisible newcomer. Thus ended the fleeting existence of this new particle, lasting only 10^{-10} seconds. Yet those brief moments caused great excitement among physicists!

When scientists began studying photographs of the traces left by new particles, they discovered something so astonishing that it was enough to make them clutch their heads in disbelief. It turned out that not just one, but *two distinct* types of elementary building blocks had been discovered: heavy K-mesons and hyperons, which were more massive than nucleons. Today, there are already more than a dozen types of mesons and hyperons. Although no one had anticipated the emergence of new particles — especially in such great numbers — and none of the existing theories had predicted them, physicists had to adapt to the new reality. They had to accept the world of elementary particles as it was.

One habit, after all, can always be replaced by another. Yet, physicists still struggle to grow accustomed to the "strangeness" of these new particles. But why were these newly discovered particles called *"strange"*? What makes them "strange"?

K-mesons and hyperons were produced in extremely short timescales — far shorter than what we usually call the blink of an eye — through strong interactions between nucleons. They also decayed into strongly interacting particles, meaning they should have disappeared just as quickly. However, in reality, these particles live a hundred trillion (100,000,000,000,000) times longer than expected! How could they not be called "strange"?



And yet, the "strange" hyperons appear to be quite closely related to nucleons. Not only do they coexist peacefully in the table of elementary particles, but they can also exist

together within the same atomic nucleus. Neutral lambda hyperons, for instance, can replace one or even two neutrons.

A hyperon does not arise within a nucleus on its own; rather, the nucleus acquires it when struck by a high-energy cosmic proton. One of the fragments from the collision carries away the hyperon as a reminder of the catastrophe. This fragment, called a hypernucleus, exists for as long as the hyperon itself — approximately 10^{-10} seconds.

However, while hyperons behave relatively well, their cousins, the heavy K-mesons, are true rebels and nihilists. They refuse to conform to the fundamental laws of the microcosm. From the moment of their discovery to the present day, experiments with K-mesons have remained at the forefront of physics.

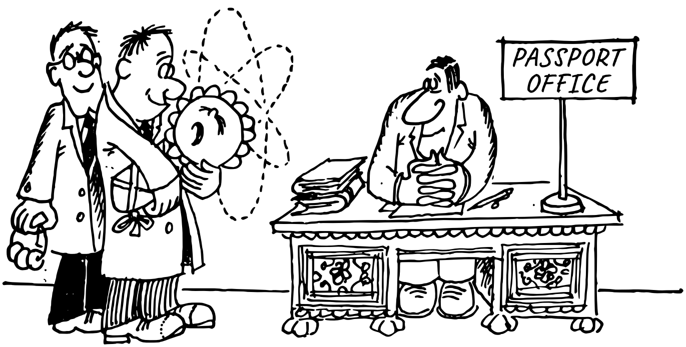
See how imperceptibly, driven by the child's question "How is everything structured?", we first found eight, and by 1960, about thirty types of matter's building blocks. The importance and necessity of the first three particles were undeniable. After some thought, six newly discovered ones were also given a role. But even today, no application has been found for thirty particles!

Nature's boundless generosity was perplexing. By now, no one dared to claim how many elementary particles should exist in nature. When will the list of matter's building blocks be complete? Could it already be finished? Or is it only just beginning?

A Restless Domain

Unexpectedly, physicists became owners of a vast and "multi-sectoral enterprise" of elementary particles. There were massive nuclear nucleons and hyperons, heavy mesons and light neutrinos, mu-mesons and photons. Listing them all in detail was nearly impossible.

The number of particles grew so large that doubts arose – could they really be distinguished from one another with certainty? It was pointless to talk about the appearance or colour of hyperons. Yet, despite this, each newly discovered particle soon received its own passport. Its surname, nationality, and social status were effectively replaced by its mass, charge, and lifetime. Equally important was the particle's spin – a quantity related to its intrinsic rotation – or its magnetic moment, which directly reflected the distribution of currents within the particle.



In the plant and animal kingdoms, individuals of the

same species always differ slightly from one another in size, colour, or behaviour. Sometimes, an inexperienced botanist or zoologist might even make a classification mistake due to a specimen's significant deviation from typical species traits.

An experimental physicist, however, faces no such risk. Elementary particles of the same type are *completely identical*. All protons and all neutrons are *indistinguishable* from one another, whether produced in an accelerator or originating in cosmic rays. This means there is no need to meticulously study all their properties in each experiment — one only needs to determine to which type a given particle belongs.

A charged particle's track in a photograph serves as its passport card, allowing its mass to be determined. If the entire track fits within the image and the particle's speed is known, its lifetime can also be measured. A magnetic field reveals the sign of its charge.

All other relevant information is found in the elementary particle table, compiled using each particle's passport data. A quick look at this table immediately shows that one type of particle differs from another primarily in terms of mass, lifetime, or decay mode.

Particle masses span an enormous range — from zero for photons and almost zero for neutrinos[6] to a value of about 3200 times the electron's mass in the case of the heaviest, the omega hyperon. [7] Lifetimes vary just as dramatically, from 10^{-23} seconds for the rho meson to 10^{28}

[6] For decades, neutrinos were thought to be massless. However, experiments in the 1990s century, particularly those studying neutrino oscillations, revealed that neutrinos do have a tiny, *non-zero* mass. This discovery, which earned the 2015 Nobel Prize in Physics, confirmed that neutrinos can change between different "flavors" (electron, muon, and tau neutrinos), a phenomenon only possible if they have mass. While their exact masses remain unknown, they are incredibly small — far lighter than any other known particle. – DM

[7] As of 2025, the heaviest elementary particle is the top-quark with a mass approximately 340,000 times the mass of an electron. Discovered in 1995 at the Fermilab Tevatron collider. Its mass is so large that it decays almost instantly (in about 5×10^{-25} seconds) into lighter particles. – DM

years for the proton!

But what a dreary monotony in the "Electric Charge" column! Neutral, negatively charged, and positively charged — that is the entire range of variation. True, the words "negatively" and "positively" charged indicate only the sign of the charge and say nothing about its magnitude. Perhaps this magnitude varies as widely as mass and lifetime?

For charge, however, nature has made a pleasant exception. A particle either has no charge at all, or its charge is *exactly* equal to the charge of the electron.[8]

As we browse the table of elementary particles, we notice that some particles are lighter, others heavier; some live long, while others exist only for a fleeting moment. But the table says nothing about their turbulent lives, filled with astonishing events.

The elementary building blocks of matter are born either in nuclear catastrophes, when particles of enormous energy collide, or in the "calm" process of radioactive decay. Unstable particles end their "lives" by decaying into lighter ones. Sometimes they are captured by atomic nuclei of the substance in which they come to rest.

Elementary particles undergo transformations when interacting with each other. Moreover, each particle does so in its own unique way. This is where their fundamental qualitative differences manifest.

[8] At the time this was written, it was believed that all observed elementary particles carried charges that were either zero or an integer multiple of the elementary charge (the charge of the electron). However, the discovery of quarks and subsequent experiments revealed that quarks possess fractional charges of $\pm 1/3$ or $\pm 2/3$ of the elementary charge. Despite this, free quarks have never been observed in isolation due to a phenomenon known as color confinement, meaning that all directly observable particles still adhere to the integer charge rule. – DM

The Realm Of Energy

Our account of the discovery of elementary particles paused in 1960 when physicists had identified about 30 types of the simplest building blocks of matter, with no doubt that their number could soon double.

By this time, elementary particle physics had ceased to rely solely on data from cosmic ray research. Powerful accelerators had begun operating in scientific laboratories.

As early as 1949, the most powerful accelerator in the world at the time began operation at the Institute for Nuclear Problems of the USSR Academy of Sciences. With its help, physicists gained many new insights into the properties of atomic nuclei and the interactions of fast protons and neutrons with matter. The experimental results obtained enabled Soviet scientists, within a few years, to solve the problem of the peaceful use of atomic energy. The launch of the world's first nuclear power plant in Obninsk in 1954 marked the beginning of a new era in energy development.

In April 1957, a new accelerator — the synchrophasotron[9] — was commissioned at the Joint Institute for Nuclear Research in Dubna, near Moscow. It was capable of producing protons with energies up to 10 billion electron volts.

[9] A type of synchrotron, but the name "synchrophasotron" was used to emphasise its phase-stabilising principle. – DM

No other laboratory in the world had yet produced particles with such high energy. Scientists from socialist countries managed to probe even deeper into the mystery of matter's structure. This accelerator led to the discovery of

several new elementary particles, including one from the hyperon family: the anti-sigma-minus hyperon.

All particles can be created in collisions between any two particles, such as high-energy protons with atomic nuclei. The location of these collisions — whether in space, at the boundary of Earth's atmosphere, or within an accelerator's target — makes no fundamental difference. However, cosmic protons have far greater energy than those accelerated in even the most powerful machines. On the other hand, working with laboratory beams of pi-mesons is far more convenient than capturing them from cosmic rays.

As physicists refined the properties of particles, they noticed that most known particles had lifetimes longer than 10^{-14} seconds. The shortest-lived among them was the eta-meson, which existed for only about 10^{-19} seconds.[10]

Yet scientists were puzzled: why had no particles been found with lifetimes in the range between 10^{-19} seconds and the so-called "nuclear time" of 10^{-22}-10^{-23} seconds — the minimum time required for a newly formed particle to manifest its existence? However, no sooner had physicists asked this question than a particle with such an unimaginably brief lifetime was discovered!

Two years before his death, at the age of fifty, Enrico Fermi conducted an experiment at the low-energy Chicago accelerator to investigate the details of pi-meson interactions with nucleons. The results were astonishing! At a certain pi-meson energy, its interaction with the proton changed character. This resembled the sharp rise in

[10] The shortest-lived particle known today is the *Z*-boson, with a lifetime of approximately 3×10^{-25} seconds. The *Z*-boson, a carrier of the weak nuclear force, decays almost instantly into other particles, making it one of the most ephemeral entities in the subatomic world. It was discovered in 1983 at CERN. – DM

electromagnetic wave intensity when the frequency of a generator reaches resonance with that of a transmitting antenna.

Here, the kinetic energy of the pion and the potential energy of its interaction with the proton entered into *resonance*. For a time comparable to the "nuclear" time (10^{-22}–10^{-23} seconds), the meson was "trapped" near the proton, forming a new complex particle. However, at that time, this resonance was not yet considered a distinct particle.

When more powerful accelerators were built, proton energies became so high that collisions with nucleons produced several different types of particles simultaneously. Physicists wondered: what if these were fragments of some primordial, superheavy particle that decayed within the "nuclear" time?

By measuring the scattering angles and energies of all the resulting particles, physicists could calculate the mass of this "proto-particle." After performing these measurements and calculations, they concluded that such "proto-particles" indeed exist. They decay within 10^{-23} seconds into familiar nucleons, hyperons, and mesons. These new particles were named "resonances," reflecting the history of their discovery.

It turned out that resonance formation was not an exceptional occurrence but a general property of strongly interacting particles. At sufficiently high collision energies, two, three, or more secondary particles could form

unstable complexes.

The first discovered resonances were complexes of two particles. Some decayed into two pions, while others decayed into a kaon and a pion. Later, new, more complex combinations were found.

So many experimentalists became involved in the search for new particles that most resonances were discovered simultaneously in multiple laboratories.

"It is unfortunate that Fermi, who in 1953 discovered the first case of so-called hadronic resonances, was unable to witness the continued triumphant development of this field and the appearance of hundreds of resonances in the tables of elementary particles," wrote his student, Soviet academician Bruno Pontecorvo, in his memoirs about Enrico Fermi.

So, how many elementary particles are known today?

It is time to take stock, though this is not an easy task. The relatively modest table of elementary particles compiled by physicists by 1960 has now been swept away by the flood of newly discovered particles — resonances — within a short period.

The 30 elementary particles previously known to us, which until a few years ago seemed to deserve exclusive attention, have turned out to be merely the relatively stable and lighter members of an enormous family of formations. Yet even today, experimentalists continue to report the discovery of more and more new particles, all of which still fall into the category of resonances.

Even specialists in elementary particle physics find it difficult to determine the exact number of all fundamental building blocks of matter. Their count has already exceeded 200![11] Currently, a dedicated international centre publishes a 100-page journal each year, providing information on newly discovered particles.

[11] As of 2025, the number of known elementary particles exceeds 300, most of which are resonances. – DM

So, in their quest to answer the question, "*How is everything structured?*" physicists have come a long way. Initially, there was a complex picture of matter's composition — about ninety "elementary" atoms. This was replaced by the simplest model, consisting of just three fundamental building blocks: the proton, neutron, and electron. And finally, they arrived at the discovery of the astonishing world of elementary particles.

Journeys into space, to the depths of the seas and oceans, are fascinating. But no less captivating is the journey into

the depths of matter!

Alpha particles first allowed Rutherford to probe space down to a distance of 10^{-13} centimetres. And modern high-speed atomic projectiles now enable us to explore distances as small as 10^{-15} centimetres!

In addition to new spatial scales, elementary particles have also introduced us to entirely new scales of energy.

After the discovery of nuclear fission reactions, physicists were astounded by the amount of energy released when a single uranium nucleus splits. But in the collision of a proton with nucleons in the Serpukhov accelerator, the energy transferred and absorbed is a thousand times greater!

In an instant, newly formed nucleons and antinucleons, mesons and hyperons fly off in all directions from the target. In an instant, the heaviest of all particles — resonances — decay into individual particles. Each collision brings to life this restless, dynamic, ever-changing world, whose colours and diversity depend entirely on energy. It is energy, and energy alone, that serves as the nurturing medium where the extraordinary "mirages" of the microcosm briefly bloom.

2 The Last Matryoshka?

> "In this world —
> I know — there is no end to treasures,
> But it is most enlightening to peer inside
> The very core of things,
> Right into the heart of things. "
>
> *L. Martynov*

The Phoenix

> "In its original sense," writes Academician M. Markov, "the term '*elementary particles*' should have referred to the simplest building blocks of matter."

But were physicists too hasty in giving this name to protons, neutrons, and other particles? Can heavy, instantly decaying hyperons and resonances truly be considered the *fundamental constituents of matter*?

Doubts had troubled scientists for a long time. In 1950, when only nine building blocks of matter had been discovered, Enrico Fermi remarked that "this is already a large enough number to cast doubt on the elemental nature of at least some of them."

Physicists' skepticism only grew when, in just five years, three dozen building blocks expanded into two hundred.

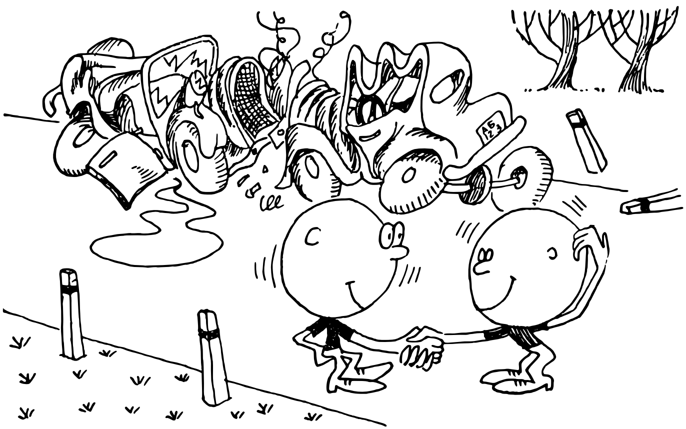
> "The concept of elementarity has lost its original meaning," summarised theoretical physicist and Nobel laureate Academician I. Tamm regarding the "explosion" of particle discoveries. "At present, we cannot distinguish truly elementary particles from composite ones."

Cannot distinguish them? But that seems simple! If a free neutron undergoes radioactive decay into a proton, electron, and neutrino, then it must be composed of these three, much like a house of cards built from individual cards. Similarly, a mu-meson *must* be made up of an electron and a neutrino.

But is this truly the case? If something is composed of separate parts, then, with sufficient effort, those parts should always be detectable. An atom, for instance, consists of electrons and a heavy nucleus. By applying just a few dozen electron volts of energy, one can ionise an atom, removing the required number of electrons. Or, as Rutherford once did with alpha particles, knock out the nucleus.

Finally, by investing a million times more energy, even the atomic nucleus — packed with protons and neutrons — can be split apart.

In short, every entity once declared elementary has, over time, been dissected by physicists, much like a wooden Matryoshka doll. Peering inside, they have consistently discovered smaller, even more fundamental building blocks of matter.



But how can an elementary particle be broken apart? How can we determine, for example, what a proton is made of? The history of searching for ever simpler building blocks of matter seems to suggest the most natural answer: strike the elementary particle as hard as possible.

Some physicists do exactly that. They bombard a target made of hydrogen-containing material with high-energy protons from particle accelerators. In the late 1960s, exper-

iments at the Dubna synchrophasotron studied collisions between protons with energies of 10 billion electron volts and other nucleons. Today, in Batavia, USA, accelerator targets are struck with protons at energies 40 times higher.

Yet, despite all these efforts, no experiment has ever succeeded in knocking out a "component" of an elementary particle or detecting its fragment. In all nuclear reactions, the particle has behaved as an indivisible whole. It turns out that even the most violent collisions in the microcosm occur without a single "casualty."

So, could it be that elementary particles cannot be divided at all? That they are not just a simple house of cards or a Matryoshka doll?

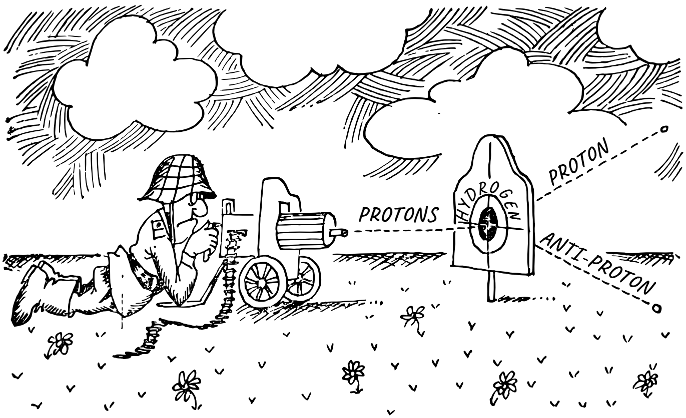
In response to this question, the Director of the High Energy Laboratory at the Joint Institute for Nuclear Research, Corresponding Member of the USSR Academy of Sciences, A. Baldin, said:

> "When discussing the structure of matter, we rely on the familiar idea that a whole can be divided into separate parts. However, if we attempt to break apart an elementary particle, new particles emerge instead. The most astonishing thing is that from this catastrophe, the original particle reappears, like a Phoenix from the ashes — unharmed and identical to its initial state!"

Playing by the Rules

Let us imagine that we are near the proton accelerator in Dubna. Everything is ready for a complex experiment. A hydrogen target is secured. Current is supplied to the accelerator's magnets. A sound signal, a red warning light on the display — everyone leaves the experimental hall.

In this hall, an unseen yet instrumentally recorded great "mystery" of the microworld is about to unfold — the birth of elementary particles at the moment of collision between accelerated protons and the protons of the target.



The duty operator switches on the high-frequency generator, and the accelerator begins to operate. With each "exhalation," a batch of fast protons pierces the target. A collision occurs — instantaneously, the equipment identifies pairs of newly born twins. These could be a proton and an

antiproton, a neutron and an antineutron, or resonances and fast pi-mesons.

When atomic projectiles lacked sufficient energy to create antinucleons, antiprotons, and antineutrons, everything was straightforward. The reaction followed the law of energy conservation and another fundamental principle — the conservation of nucleon number.

However, once accelerated protons gained enough energy to produce antinucleons, confusion arose. The law of nucleon number conservation no longer held in nuclear reactions. It seemed that the creation of new particles was governed solely by energy conservation, while everything else appeared entirely chaotic.

Energy, energy, and more energy! Could it be that in the microworld, energy reigns supreme, unrestricted by any laws or rules?

At first glance, this seemed to be the case. Two protons collide, and as a result of the interaction, several new protons appear, along with — much to the delight of experimenters — an entire swarm of antiprotons, neutrons, antineutrons, and mesons. It resembled a game of roulette — throw in a proton and wait to see what comes out in return.

Before long, physicists noticed that this seemingly random game was not entirely unpredictable. It had its own strict rules.

According to these rules, physicists assigned each nu-

cleon a value of +1 and each antinucleon a value of –1. Mesons were given a value of 0. With this system, even a schoolchild could verify that in every reaction, the total value before a collision was always equal to the total value after the collision.

The points assigned to nucleons, antinucleons, and mesons were named the *baryon charge* of these particles by physicists. The discovered rule of the game became known as the *law of baryon charge conservation*. No matter how protons collided — with other protons, neutrons, or gamma quanta — the number of newly formed nucleons always equalled the number of newly formed antinucleons.

> "This law," wrote Professor Ya. Smorodinsky, "reflects a fundamental property of atomic nuclei — their stability. If this law were even slightly violated, protons or neutrons in nuclei would disappear, transforming, for example, into positrons, neutrinos, or mesons. Our very existence depends on the fact that the law of baryon charge conservation is never broken."

There are other rules and laws governing the birth of elementary particles, but we will not dwell on them now. Listing them would shed little light on the issue at hand. Even after discovering these rules, physicists still do not fully understand the endless game — *how many particles will appear, and of what kind?*

But the most fundamental question remains unanswered:

where do all these particles come from when collisions occur?

Point or Not a Point?

Strike a carpet with a stick, and hundreds of dust particles will dance in a beam of sunlight. No one wonders where they came from — it is clear that they were hiding in the carpet's fibres until the stick dislodged them.

But can we ask where the particles produced in accelerator collisions — such as those between protons — were hiding before they appeared?

No, this question is meaningless. They were *not* hidden anywhere; they were *born* at the moment of impact. Consider this: when a proton in a radioactive nucleus transforms into a neutron, an electron, and a neutrino, we do not say that the last two were hiding in the nucleus. They simply emerged in the process of transformation.

Physicists have long known that a proton can turn into a neutron and vice versa. Pi-mesons decay into lighter particles; heavy resonances decay into "strange" particles and ordinary ones; hyperons and K-mesons decay into protons and neutrons. At the same time, high-energy protons, colliding with nucleons in a target, generate resonances, hyperons, nucleons, and mesons.

This mutual convertibility of elementary particles — their ability to be created and annihilated — inevitably led

to the idea that their properties were interdependent. It began to seem as though the very nature of one elementary particle was shaped by all its counterparts in the microcosm.

Gradually, the idea that "everything consists of everything" became commonplace. The American theorist D. Chu aptly named this concept "nuclear democracy," which governs the family of strongly interacting particles.

Yet, thinking in this way, physicists found it increasingly difficult to ignore the sense that particles, which theory describes as point-like, actually possess structure and spatial extent.

Protons and neutrons — these particles that never truly disappear but only *transform* into one another — seem convincingly point-like. But only under one condition: if viewed from afar. What if we take a closer look?

Protons accelerated to immense energies were fired at a target. They approached the proton-target so closely that this supposed "point" unexpectedly revealed unfathomable depths within it. As Professor Ya. Smorodinsky vividly put it, the proton turned out to be more like a turbulent vortex, where pi-mesons — also called pions by physicists — are constantly being born and annihilated.

But that is not all! Besides pions, nucleons and antinucleons also emerge and vanish in the vicinity — or perhaps even inside — what we call the proton.

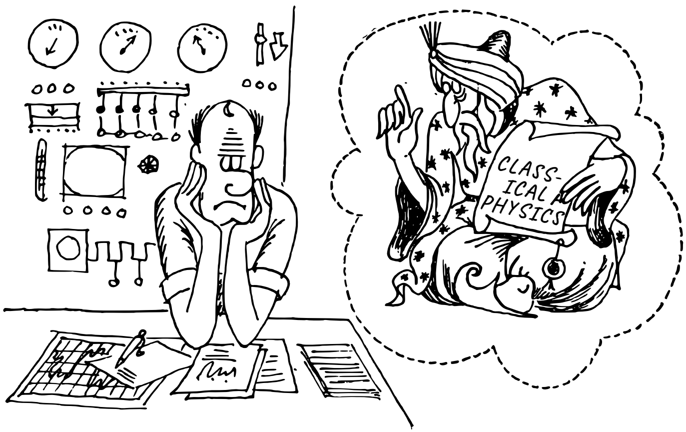
So, does this mean that the particles we call elementary

are ultimately infinitely complex and perhaps even have a definite size?

For now, theory cannot answer this question.

Look into textbooks published fifteen years ago. There, you will read that elementary particles cannot, in principle, have size because they always participate in processes as indivisible wholes: they do not split or deform. This is not a mistake by the author of the book. This assertion is fundamental to quantum mechanics itself.

What, then, forbids us from thinking of an extended particle, from constructing any kind of "pictures" of particles, or from assigning them structure?



Imposing one's own rules in a foreign domain is risky. Yet, we are delving deeper and deeper into the unusual world of elementary particles with the "rules" of classical

physics, which do not belong there. And classical physics, like a well-meaning but "outdated" Old Man Hottabych[12], whispers: if an object manifests itself only as a whole, then it must be absolutely solid.

The discussion about whether particles are point-like or not can be considered closed within the framework of theory. Any further reasoning on this topic is cut short by the theory of relativity. According to its principles, an absolutely rigid body can have neither structure nor size. After all, if two absolutely rigid bodies were to collide, the impact would have to be transmitted instantaneously throughout their entire volume. Instantaneously means faster than the speed of light. But the entire theory of relativity is based on the fact that no speed can exceed the speed of light.

> "An elementary particle in quantum mechanics," says Academician M. Markov, "is a point-like particle in the literal sense of the word."

That is the entire answer. Unfortunately, even modern theory cannot explain anything to us. It emerged from the depths of quantum mechanics and, following in its footsteps, continues to repeat the "fairy tale" of the point-like particle.

The Language of Scattering

As is well known, no matter how many times you repeat "sherbet, sherbet," your mouth will not become sweet. All these discussions about the structure and extent of parti-

[12] Old Man Hottabych refers to the character from *The Old Genie Hottabych*, a Soviet children's novel by Lazar Lagin, published in 1938. The book tells the story of a boy who frees an ancient genie (Hottabych) and the humorous culture clash that follows as the genie, with his outdated magical worldview, struggles to understand modern society. You can get the English version here. – DM

cles would not be worth a fig if these properties could not be experimentally “probed.”

Sometimes, we find ourselves unable or not allowed to open a box or casket, yet we are certain that something is inside. To guess its contents, we shake and rattle the box, listening to the sounds it produces.

To check for voids or cracks in a large casting, we use X-rays or gamma rays to scan it.

The challenge faced by researchers of elementary particles is far more complex. A particle is not a box with walls but a sophisticated system with distributed charge and currents. Studying the structure of an elementary particle means determining the distribution of all its charges and measuring its electromagnetic radius.

But is it possible to carry out such a delicate and extraordinarily precise operation?

Let us recall how the atomic nucleus was discovered. Before Rutherford’s experiments, atoms were envisioned according to Thomson’s model — a positively charged sphere with electrons “floating” within it. Then, using alpha particles, scientists managed to probe the atom and detect its heavy nucleus.

Experimenters observed the behaviour of alpha particles — these natural atomic projectiles — as they passed through thin films of various substances. Most of them continued almost unchanged in their direction of motion. However, some were deflected by 90° even 180°. The

unmistakable conclusion was drawn immediately: these particles had encountered a *tiny yet heavy* object.

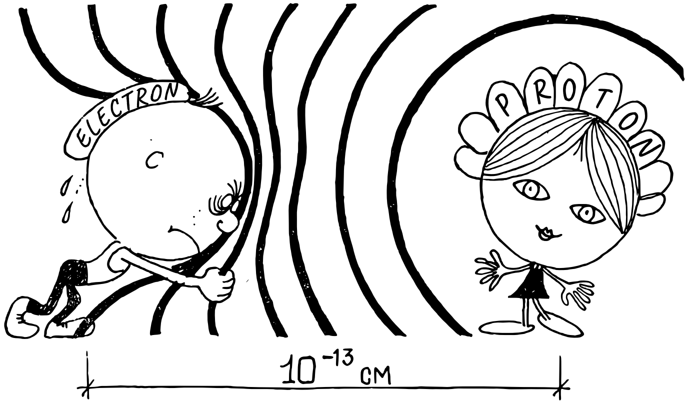
The universal language of scattering could have been applied in our case as well. However, such a coarse probe as an alpha particle, composed of two protons and two neutrons, was unsuitable for this purpose. A single fast nucleon was also inadequate, as strong nuclear interactions with the target particle would immediately begin, leading to the creation of new nucleons and mesons. Under such conditions, it would be impossible not only to analyse the structure of the particle but even to determine whether it was the original particle or a newly formed one.

Attempts were made to "scan" protons using light particles — photons. However, this method also proved unsuitable for studying the fine structure of an elementary particle. To approach a proton within a distance of less than 10^{-13} centimetres, a photon needed to possess extremely high energy. In such cases, collisions with the proton would again result in the formation of resonances and other particles.

The most suitable probe for this purpose turned out to be the first elementary particle ever discovered by physicists — our old acquaintance, the electron.

Electrons interact with other particles solely through electromagnetic forces, which means that strong interactions with target protons are ruled out. Moreover, an experiment with electrons can be designed in such a way that only those particles transferring the minimal possible

energy to the proton are recorded. In other words, cases involving the creation of new particles can be excluded.



Thus, projectiles reveal what they encounter on their path through the language of scattering.

The laws governing the scattering of a point charge by another charge have long been established in the theory of electromagnetic interactions. If we assume that the electron is a point-like particle, then its scattering by a proton will show how they interact with each other. Any deviation from the expected scattering behaviour of point charges would indicate that the proton has an internal structure.

But such a tale is quickly told, while the task itself takes much longer to accomplish. It is easy to explain in principle how to study the structure of elementary particles, but before conducting such experiments, scientists first had

to learn how to produce electrons with enough energy to approach protons almost up close. "Up close" in this case means at a distance of less than 10^{-13} centimetres.

> "As a matter of fact," noted Corresponding Member of the USSR Academy of Sciences D. Blokhintsev, "progress in studying problems such as nucleon structure is just as difficult as exploring the farthest regions of the universe. The difference is that astrophysics relies on complex telescopes, while atomic physics depends on complex accelerators."

Electronic Assault

In 1954, a new linear electron accelerator was put into operation at Stanford University in the United States. That same year, a group of experimental physicists led by the American scientist Robert Hofstadter completed preparations for an assault on nucleons.

Enrico Fermi once remarked:

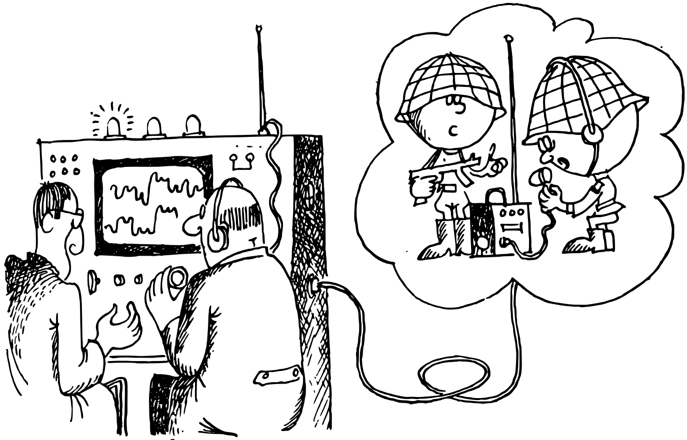
> "At every stage of scientific development, we call elementary those particles whose structure we do not yet know and which we consider to be point-like."

However, even at that time, as physicists sought to understand the mechanism of nuclear forces, they suspected that elementary particles had a highly complex structure. Nucleons were imagined as "bare" particles wrapped in a "coat" or cloud of pi-mesons. And these seemingly naïve

ideas had some justification.

Boys playing war games build snowball forts around themselves before hurling their ammunition at imaginary enemies. The mass of each snowball determines the distance from which they can hit a “foe” — beyond a certain range, the game loses its excitement.

Similarly, the mass of pi-mesons defines the range of nuclear forces — the distance over which protons and neutrons can interact. Furthermore, the movement of charged mesons within this cloud generates the magnetic moment of nucleons. This alone is enough to consider nucleons and mesons structurally inseparable from each other. But could high-energy electrons detect this meson coat?



And so, the assault began. Electrons from the Stanford accelerator, reaching energies of up to 550 million electron

volts, plunged into the unknown depths of matter. The experimental apparatus began receiving the first reports from the electronic landing force inside the target.

Physicists eagerly decoded the incoming data, translating it into graphs and tables, recording their findings in formulas. Somewhere within the range of nuclear forces — precisely at a scale of 10^{-13} centimetres — the electronic assault was expected to detect the forward outposts of the nucleons: the charged cloud of pi-mesons.

The initial results, however, were disappointing. Electrons scattered off protons as if they were point charges. But this early setback did not deter the scientists. They decided to rearm, refining their apparatus and improving its precision.

Once again, a beam of electrons was directed at the target. Once again, anticipation and tension filled the air. What was happening in the seemingly endless depths of matter? What were the electrons encountering? A dimensionless point, or an extended charged structure?

Perseverance and exceptional experimental skill prevailed. The electrons detected the meson cloud around the proton. This was a groundbreaking discovery, a major milestone in physics. It confirmed that *elementary particles possess internal structure*.

In recognition of this achievement, Robert Hofstadter was awarded the Nobel Prize in 1961 for his work in uncovering and studying the electromagnetic structure of

nucleons.

However, this did not mean that all questions were immediately resolved. Many physicists remained sceptical, reluctant to interpret Hofstadter's findings as proof of the proton's size and structure. An alternative explanation still lingered: what if the electron itself was *not* point-like, and the laws of electromagnetic interactions changed at distances of 10^{-13} centimetres between charges?

Definitive proof of the spatial extent of nucleons could only come from observing the interaction of two point charges positioned closer than 10^{-13} centimetres.

At this stage, physicists turned their attention to mu-mesons — failed contenders for the role of nuclear force carriers. Like electrons, mu-mesons interact either electromagnetically or weakly. Since the weak interaction is thousands of times weaker, one could expect a mu-meson meeting an electron to follow the electromagnetic rules governing the interaction of two charges.

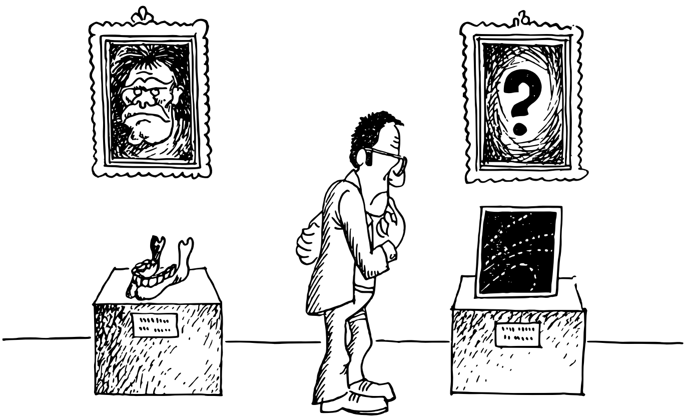
The key to determining nucleon structure lay in studying the scattering of mu-mesons on atomic electrons. In experiments where electrons and mu-mesons came even closer than 10^{-14} centimetres, the behaviour strictly adhered to the predictions of electromagnetic interaction theory for point charges.

This meant that Hofstadter's experiments could only be explained by accepting that *elementary particles are complex structures with a definite size*. But how do scien-

tists today conceptualise the electromagnetic structure of protons and neutrons?

Physicists studying the micro-world cannot be expected to reconstruct the precise internal structure of an elementary particle based solely on scattering experiments.

Much like how a skull can provide insight into many facial features, experimental data allow scientists to infer particle structures. Many may have seen Mikhail Gerasimov's original sculptures[13] in the *Museum of Anthropology* — his reconstructions are highly accurate because there is a strict correlation between the size and shape of each skull bone and the corresponding facial muscles.



A physicist works much like a palaeontologist who must reconstruct the appearance of a fossilised creature based on a single tibia or jawbone. Naturally, the reconstructed image of a dinosaur may not match every detail of the

[13] Mikhail Mikhaylovich Gerasimov (1907–1970) was a renowned Soviet archaeologist and sculptor, famous for his pioneering work in facial reconstruction from skulls. Using his deep understanding of anatomy and anthropology, Gerasimov developed a method to recreate the facial features of historical figures based on their skeletal remains. His reconstructions, displayed at the Museum of Anthropology and Ethnography in St. Petersburg, include lifelike portraits of ancient rulers, warriors, and other individuals from archaeological sites. – DM

creature that lived millions of years ago, nor is such precision expected. However, in broad terms, we obtain a reasonably accurate picture.

So, what exactly did R. Hofstadter discover? He found that "elementary" protons and neutrons have a highly complex structure. Most of their mass is concentrated within a spatial region of approximately 0.8×10^{-13} centimetres in radius. Surrounding this core is a diffuse meson shell, which physicists refer to as either a *meson cloud* or a *meson coat*. The density of this meson shell decreases as one moves away from the centre.

The charge of the proton is also unevenly distributed. Only slightly more than ten percent is concentrated in the central region, while the rest is spread throughout the meson cloud.

Previously, it was thought that a neutron, despite being neutral on average, contained both positively and negatively charged regions. However, this model of the neutron was disproven. When the "electronic assault" probed closer, it found no sign of a charged meson cloud — no electrical outpost at the neutron's boundary. Could the charge be hidden deeper inside?

Today, electrons with extremely high energies penetrate the neutron to distances as small as 0.2×10^{-13} centimetres, yet no charged region has been found. Could the neutron be a point-like particle?

No, that is not the case. It cannot be said that electrons,

reaching such extraordinary depths, encountered no resistance. On the contrary, precisely where the meson cloud should be, the incoming electrons suddenly experienced a magnetic interaction.

So, does the neutron also have a meson cloud? Yes. It is the same size as the proton's, but it is electrically neutral. This cloud may consist of neutral pi-mesons, or perhaps of pairs of negative and positive mesons.

These results made physicists question whether other particles were truly point-like. But how could this be tested? It is one thing to study a long-lived nucleon, but how does one investigate a particle that exists for less than 10^{-10} seconds? What about those that appear for only 10^{-19} seconds? How can they be turned into a target for electrons?

And yet, scientists have recently found a way to "measure" the pi-meson. It turns out that it is not point-like either but has a *definite* radius of about 0.8×10^{-13} centimetres. It is reasonable to assume that all particles experiencing strong interactions are of similar size.

But what about the mu-meson, the electron, and the neutrino? The mu-meson and electron behave as two point-like charges even at distances smaller than 10^{-14} centimetres. This leads to only one conclusion: if they do have a size, it must be *smaller* than 10^{-14} centimetres.

What comes next?...

So, the "legend" of point-like particles no longer exists. Now, there is no need to prove that at least strongly

interacting particles are complex systems with a finite electromagnetic radius.

But what, then, is an elementary particle? Is it the final "matryoshka" in the structure of matter, or is there something beyond?

The groundbreaking results of R. Hofstadter's experiments on high-energy electron scattering led to the emergence of composite models of elementary particles.

One of the most successful composite models, proposed by the Japanese physicist Sakata, identified the lambda hyperon, proton, and antineutron as the fundamental building blocks from which all other particles were constructed. This model further developed the idea of the renowned theorists Fermi and Yang, who had first proposed that the elementary particle, the pi-meson, could be made of a nucleon and an antinucleon — that is, of particles several times heavier.

The successful ability of this model to describe various nuclear reactions and predict certain particle properties triggered an explosion of “fashion” for composite models. Soon, nearly every theorist (and even non-theorist) considered it a matter of honour to create their own, sometimes extravagant, model of an elementary particle. However, the discovery of new particles and the study of their interactions gradually dismantled these ephemeral constructions one by one. Even Sakata’s serious hypothesis did not withstand the test of time, as its choice of fundamental particles proved unsuccessful.

Nevertheless, the mathematical framework of this model revealed new regularities in the world of elementary particles. Sakata’s idea of constructing them from three fundamental building blocks was the immediate precursor to the quark model of matter, which will be explored in the next chapter.

Interestingly, as early as the beginning of the 20th century, when only one elementary particle — the electron — was known, J.J. Thomson had already attempted to understand its structure. In a lecture aptly titled *Beyond the Electron*, he stated:

> “Perhaps some of you are ready to ask me: should we really go beyond the electron? Would that not be too far? Shouldn’t we draw a boundary somewhere? The charm of physics lies precisely in the fact that it has no rigid and fixed boundaries.”

> "In physics, every discovery is not a final limit but rather an avenue leading to an unexplored land. No matter how long science exists, there will always be an abundance of unsolved problems, and physicists will never risk becoming unemployed."

In his book published in 1958, Academician M. Markov spoke of the extraordinary complexity of the modern concept of an elementary particle, where each particle

> "begins to appear as a complex composition of all 'elementary' particles. If, indeed, all particles are necessary to construct the image of each one, then it is natural to seek some other 'material' — one more elementary in the sense that it would be common to the entire list of fundamental particles."

3 The New Linnaeus

Did not stumble in this landslide,
Did not falter, touching the mystery,
Unravelled the truth of every being
Among billions of electrons.

P. Antokolsky

Who Is Who?

The picture of matter's structure, painted neatly with three pure "colours" — the electron, proton, and neutron — was as simple as a child's drawing.

Its composition, determined by the structure of the atom and its nucleus, was easily interpreted through quantum mechanics. It seemed that by merely adding a few more details related to the nucleus and its nucleons, the picture would be complete.

However, the discovery of the vast world of elementary particles shattered this hope. Yesterday's masterpiece turned out to be merely a preliminary sketch for the future painting of matter's structure.

If one were to simply place the hundreds of discovered particles onto this picture, the result would be nothing more than a chaotic, confusing, and overwhelmingly complex scene. Clarity would emerge only if each particle found its rightful place in the overall composition — when the interconnections between all individual elements of the whole became visible.

But what should guide scientists in their search if even the most primitive "classification" of elementary particles does not exist? Perhaps understanding the social order of the micro-world's citizens requires uncovering the true principle of "elementarity" among particles?

However, modern theory still speaks of point-like particles and, in this sense, does not "see" the difference between the light electron and the heavy resonance. Yet this difference was strikingly obvious.

Leptons — such as the electron, muon, and neutrino — do not participate in strong interactions and have *no* detected internal structure.

In contrast, the vast army of strongly interacting particles — including nucleons, heavy mesons, hyperons, and resonances — follows entirely different laws and principles. Most of these particles decay into lighter ones. The discov-

ery of complex electromagnetic structures in nucleons and pions further strengthened scientists' suspicions about the "non-elementary" nature of these particles. However, lacking the means to prove this definitively, physicists simply stripped them of the title "elementary" and instead began referring to them as "fundamental" particles.

A comparison of the discovery dates of different particles reveals an interesting trend: the number of known leptons has remained almost unchanged in recent times, whereas the group of fundamental particles has grown significantly — like an ever-active volcano in constant eruption. This expansion is primarily driven by the discovery of new resonances. The relentless outpouring of scientific data on newly found particles threatened to overwhelm high-energy physics and make navigation through the world of elementary particles increasingly difficult.

Relativistic quantum theory, which attempted to describe the world of elementary particles based on a few axioms and principles, was unable to channel this overwhelming flow into a well-defined framework.

This led to the emergence of a new theoretical approach. Following this direction, scientists discovered order within the world of elementary particles and uncovered hidden patterns, relying solely on experimentally known properties of particles, such as charge, mass, and so on.

Strange Exhibits

The list of two hundred elementary building blocks of matter, compiled by physicists, resembled a herbarium created by someone unfamiliar with plant classification. This hapless botanist, assigning absolute importance to any differences between plants, would have given each of his collected specimens a separate place.

The merit of Carl Linnaeus, the creator of plant classification, lay not only in selecting the key traits that determine a plant's belonging to a particular species but also in identifying differences that could be disregarded when grouping species into families and families into orders.

But is it possible to create a classification system for elementary particles? *Which differences between particles can be ignored to group them together?*

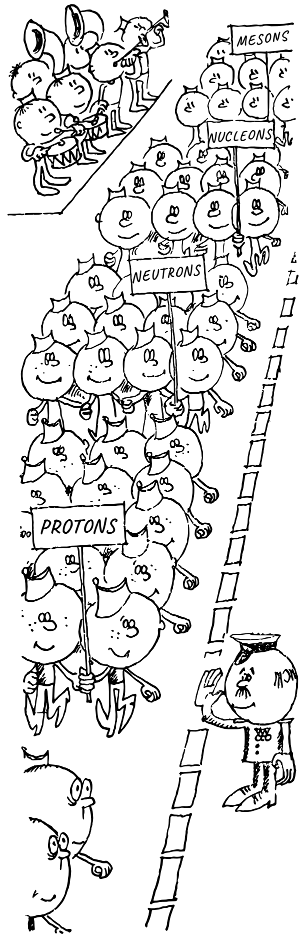
Physicists already knew that in strong interactions be-

tween a proton and a neutron, a proton with another proton, and a neutron with another neutron, there was no difference. The forces acting between these pairs of particles were identical.

These experimental facts led Heisenberg to a groundbreaking idea. He was the first to realise that if one ignored the proton's positive electric charge and the neutron's lack of charge, they could be considered the same particle — after all, in nuclear interactions, they are completely identical.

Just as all objects appear equally grey in twilight, the diversity of elementary particles fades slightly when one disregards the electromagnetic differences between them. A single "nucleon" colour is sufficient for both the proton and neutron, while a single "pion" colour suffices for the three pions with different electric charges.

The previously unordered "crowd" of elementary particles, divided arbitrarily into "first-second" and "first-second-third," now acquired some structure. Even this relatively small step towards classification proved useful for theorists. It immediately allowed them to establish certain relationships between the probabilities of processes involving particles within the same group.



At that time, "strange" particles and resonances had not yet been discovered. When they appeared, the "herbarium" of elementary particles swelled monstrously. Then, in 1960, Sakata's students first presented to delegates at an international conference a much more general pattern exist-

ing among elementary particles. Analysing their teacher's model, they discovered something akin to a periodic law for the fundamental building blocks of matter.

A year later, building on this achievement, two physicists — Murray Gell-Mann and Yuval Ne'eman — independently proposed a classification of elementary particles that included resonances. This classification made it possible to organise all strongly interacting particles into several large groups.

Murray Gell-Mann gave his systematics a poetic name: the "*Eightfold Way*." Why "Eightfold"? Because it was based on operations involving eight quantum numbers. He also jokingly remarked that it resembles the aphorism attributed to Buddha:

> "Yes, brothers, there exists a sacred truth that helps to tame suffering: it is the noble Eightfold Path, namely: right views, right intentions, right speech, right actions, right livelihood, right efforts, right mindfulness, right concentration."

The classification proposed by Gell-Mann and Ne'eman undoubtedly "tamed the suffering" of physicists. Chaos was eliminated. However, the question of how "correct" this attempt was — despite being guided by the most "righteous" intentions — remained open.

Following the work of Gell-Mann and Ne'eman, other attempts to eliminate chaos emerged, each seeming no less "reasonable" to its authors.

This led to a peculiar situation. On the one hand, many at the time viewed the classification of fundamental particles as an unpromising field in physics. Advocates of rigorous theory considered it unworthy of a true scientist.

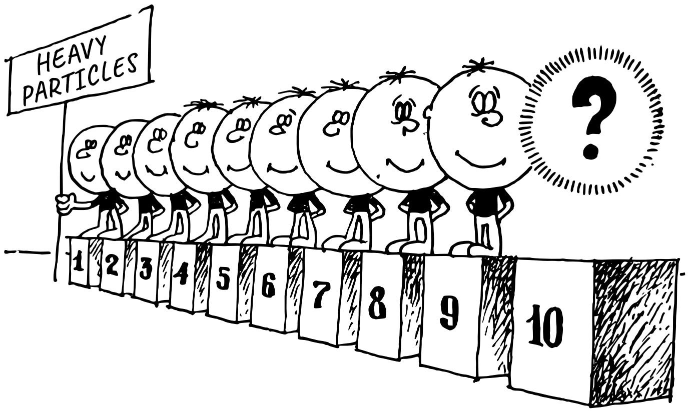
On the other hand, the growing wave of theoretical work on the subject caused "alarm and concern" in several scientific journals. It seemed that "in the light of day, theorists spoke of this field with irony, yet in the silence of night, they wrote papers about it — whose numbers were growing exponentially.

One way or another, more and more physicists became involved in the "competition" to create the best "herbarium" of elementary particles. The scientific atmosphere in high-energy physics grew increasingly tense. Which model would be recognised as the best? What would the most objective and fair "jury" — experiment —say?

But for now, experiment remained silent. Silent, like a wise sage pondering a difficult problem. Taking advantage of this pause, let us discuss what the proponents of the "Eightfold Way" expected from experiment.

Running their idea through the "mathematical operations" developed in the 19th century by the Norwegian mathematician Sophus Lie — hence known as Lie algebra — they arrived at a clear framework for the "construction" of fundamental particles. The theory dictated that particles should arrange themselves into groups of three, eight, and ten members, with each group containing particles with specific quantum numbers.

When nucleons, mesons, and resonances were distributed into these groups, it became evident that, in addition to an entirely empty group of three, one position in the group of ten heavy particles was also unoccupied. Who was missing?



Whoever is interested in the history of Dmitri Mendeleev's periodic table of elements knows that it included empty spaces for substances that had not yet been discovered. Moreover, Dmitri Ivanovich had already predicted the properties of these elements.

Using the rules governing the grouping of particles, it was easy to determine that the heaviest particle among the ten microcosmic "citizens" was missing. The unknown particle was named the omega-minus hyperon, and its "portrait" — mass and quantum numbers — was drawn. Later, these predictions turned out to be very close to real-

ity.

The discovered order helped connect phenomena that previously seemed unrelated in theoretical physics and enabled the calculation of nuclear reaction probabilities involving particles from the same group. For the first time, it became possible to theoretically determine, with great accuracy, the crucial ratio of neutron to proton magnetic moments.

Nevertheless, despite these successes, the "gap" in the ten-member group of heavy particles cast doubt on the correctness of the classification. Experimental physicists, armed with the predicted "portrait," were actively searching for the omega-minus hyperon. "If it is found," wrote M. Gell-Mann at the time, "the validity of the Eightfold Way will be strongly confirmed."

However, the main shortcoming of the new classification, as many believed, lay elsewhere. While there was hope for the discovery of the omega-minus hyperon, filling an entire missing group of three particles seemed impossible.

And it was not just about the absence of three more particles. The history of high-energy physics showed that such a deficiency was fixable; it was only a matter of time. The situation was far more complex. The mathematical logic of the Eightfold Way had reserved these places for completely unusual citizens of the micro-world.

All particles known to physicists were either neutral or

carried a charge equal to that of the electron. And suddenly, a vacancy opened up for particles with fractional charge!

The candidates for these positions were particles with charges of 1/3 and 2/3 of the electron's charge. Almost no one doubted the absurdity of such a prediction. The absence of the omega-minus hyperon and the apparent implausibility of a group of three particles with fractional electric charges significantly weakened the Eightfold Way's credibility.

Under these difficult circumstances, M. Gell-Mann (and independently, Zweig) made a move analogous to the one Thor Heyerdahl had made to prove his theory of Polynesian settlement. After studying the remnants of ancient Polynesian culture, Heyerdahl concluded that the islands had been settled not from Asia, as previously believed, but by migrants from South America. Opponents of Heyerdahl's theory argued that crossing the vast Pacific Ocean without navigational instruments or seaworthy vessels was impossible. To counter this, Heyerdahl, convinced of his hypothesis, built a raft from balsa wood and demonstrated that it was indeed possible to make the journey, thus turning his opponents' main argument against them.

Deeply believing in his classification system, M. Gell-Mann proposed that these unusual particles with fractional charge not only existed in nature but were the fundamental building blocks of all other particles, including the missing one.

Thus, he connected the loose ends of his theory. And

perhaps, the trace of doubt and uncertainty that still remained in his mind found its way into the name he chose for these particles — one borrowed from a science fiction novel.

The Jury's Verdict

"Quarks, quarks, quarks" — this strange word suddenly began appearing in early 1964 in scientific and popular science journals.

When rumours about quarks first spread within the scientific community, no one could understand what they were. Even dictionaries were of no help, as the word had no meaningful physical translation from either English or German.

Everything became clear after the release of an issue of the American journal *Physical Review Letters*. In a short article, M. Gell-Mann wrote that the unusual name "quark" had been given to the three "Cinderellas" of the Eightfold Way — the very three hypothetical particles with fractional charges. By the power of a theorist's imagination, they had become the key figures in the vast society of strongly interacting particles.

Protons, neutrons, and hyperons, as well as resonances, neatly assembled from different combinations of three quark building blocks and their corresponding antiquarks, while mesons consisted of a quark and an antiquark. With their help, all the achievements of particle classification

were easily explained, including the grouping of particles into octets and decuplets.

> "It can be explained simply and clearly — even to a child," said Academician Ya. Zeldovich, "that there are 10 particles because each particle consists of three building blocks; there are three types of building blocks, and it is easy to verify that there are 10 and only 10 different combinations."

And one of these ten combinations precisely matched the predicted characteristics of the omega-minus hyperon from the Eightfold Way. Thus, in Gell-Mann's theory, quarks were not only necessary to fill the missing group but also to explain the entire classification of elementary particles.

Physics had already seen similar situations where theorists had "invented" new particles. In 1932, Pauli proposed a small neutral particle — the neutrino — to save the law of energy conservation. A year earlier, Dirac had "discovered" the positron at the tip of his pen. Neither of these hypotheses initially thrilled most physicists.

But the quark theory aimed even higher. Accepting the existence of quarks meant recognising a new form of matter — a new kind of atomism with even more "elementary entities."

The hypothesis suggesting a continuation of the tiresome matryoshka game was met with more than a cool reception. Much later, Academician V. Ginzburg wrote that "not everyone is obliged to believe in the existence of

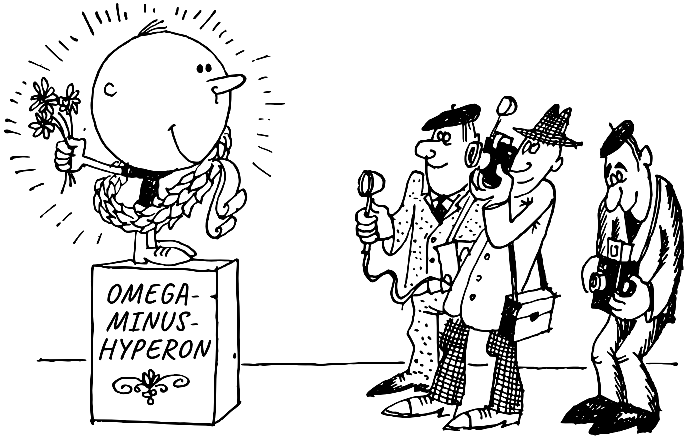
an 'infinite matryoshka': you open one doll, and inside is another — and so on endlessly." The fuss over the quark "constructor" seemed to theorists like mere amusement. And in a way, they were right.

After all, all previous attempts to build (theoretically, of course) fundamental particles out of other real particles had led nowhere. One could consider any particle to be composed of any others with suitable quantum numbers. But one could not explain its properties using these supposed building blocks. Upon forming a new particle, they seemed to lose their own "identity."

The quark model, however, insisted on precisely such a primitive construction of particles, but from three types of quarks that did not lose their individuality. This is why mere mention of the theory often brought a smile to the faces of most scientists.

It was at this critical moment that the great "judge and sage" — experiment — finally spoke. A sensational discovery spread instantly: the omega-minus hyperon had been found! The decuplet of heavy particles was complete! The real particle matched the theoretical portrait exactly!

At the Brookhaven accelerator in the United States, high-energy protons were used to irradiate a two-metre hydrogen bubble chamber. After analysing one hundred thousand resulting photographs, scientists found the particle in one of them.



The long-sought resident of the microworld was ceremoniously *installed* in its rightful place. The decuplet of heavy particles was complete. Thus, the correctness of the octet path was confirmed. Experiment had selected the best possible herbarium of fundamental particles.

The significance of the discovered order among particles is not diminished by the fact that the deeper laws of nature underlying it remain unknown. After all, D. Mendeleev himself did not know that the atomic number of an element in his periodic table corresponded to the charge of its nucleus.

The new method of particle classification, for which M. Gell-Mann was awarded the Nobel Prize, was one of the most fundamental discoveries in elementary particle physics.

But what about quarks? Does this mean they exist?

Sages never provide answers on a silver platter; they often turn them into new riddles. And one must be no less of a sage to grasp their meaning.

The discovery of the missing particle in the system did not solve the quark mystery. It neither disproved their existence nor confirmed the quark model of particle structure.

How should one interpret this answer, reminiscent of a prophecy from the Delphic Oracle? Perhaps through new theoretical constructions?

During one scientific discussion on this problem, Corresponding Member of the USSR Academy of Sciences L. Okun gave a clear response:

> "The question of whether new stable particles, particularly quarks, exist in nature can be resolved only by experiment, not by theoretical models."

Hunting for Quarks

It was difficult for Thor Heyerdahl to obtain proof for his theory. But M. Gell-Mann was not even granted such an opportunity. To prove the correctness of the quark theory, these hypothetical particles had to be discovered.

After the sensational discovery of the omega-minus hyperon, the stock of quarks rose. Quarks immediately became a coveted target for experimentalists. The hunt for quarks began. The excitement spread across many

laboratories. Quarks were sought in countries of both the Eastern and Western hemispheres. They were searched for at the synchrophasotron in Dubna, at the CERN accelerator, and in Serpukhov. They are still being searched for at the world's largest accelerator in Batavia.

But did the experimenters know what they were looking for, what these quarks looked like? Both yes and no. Only one thing was certain — they had a fractional electric charge. But as for their mass — there was complete uncertainty. According to theory, quarks could be three times lighter than a proton, but they could also weigh an entire ton!

If quarks were lighter than protons or at least less massive than the heaviest known resonance particle, they would have been discovered on accelerators long ago. Even a fractional charge would not have helped them hide from the trained eye of experimentalists. Their track in a photoemulsion would simply be thinner and fainter than that of ordinary particles with the same energy.

Everyday experience convinces us that the larger an object, the more noticeable it is and the easier it is to find. After all, locating a missing book in a room is incomparably easier than finding a tiny needle. It would seem that the same logic should apply to the search for heavy particles.

However, in accelerator experiments, quarks are not *searched for* but rather *created*. The collision energy required to bring this fantastic ghost of the microworld to life must be directly proportional to the mass of the quark.

All experiments conducted on accelerators so far have ended with negative results — free quarks have not been found. Apparently, accelerated protons still lack the necessary energy to give birth to a heavy quark.

If we discard both the extreme overestimates and underestimates of quark mass — just as in figure skating, where excessively high and low scores are ignored — the most reasonable estimate appears to be several times the proton mass.

But how can a proton be composed of three quarks, each of which is several times heavier than a proton? This problem is not as unsolvable as it seems. The nucleus of deuterium, the heavy isotope of hydrogen, consists of a proton and a neutron, yet its mass is slightly less than the sum of the masses of the proton and neutron.

In fact, the mass of any nucleus is always less than the sum of the masses of all its neutrons and protons. The difference accounts for the binding energy that holds the nucleons together in the nucleus.

Consider how easily a two-year-old child can place wooden blocks back into a box after taking them out. This is simple — the total volume of the blocks precisely matches the volume of the box. But now ask the child to fit three enormous inflated rubber balloons into a small box. He will either take it as a joke or as outright mockery. To him, the task will seem utterly impossible.

Yet this problem is entirely analogous to the one just discussed — how can we imagine a proton consisting of three heavy quarks? The box with three balloons offers a clue to the solution.

Let us release just enough air from each balloon so that all three fit into the small box. And there you have a visual model of a proton made of three quarks. It does not matter that quarks lose nearly 90% of their mass — just like the air released from the balloons — when they combine into a single elementary particle.

Could it be that quarks remain elusive because existing accelerators lack the energy needed to *inflate* the quark *balloons*?

If so, let us turn to cosmic rays. Perhaps they possess the necessary energy.

Messengers from distant worlds reach Earth's atmosphere with extraordinarily high energy. The energy of cosmic rays is a hundred million to a billion times greater than what accelerators can impart to protons. What if, up there in the upper atmosphere, in the midst of nuclear catastrophes, extraordinary quarks are being born?

Scientists meticulously examined countless photographic emulsions exposed to cosmic rays, but all efforts proved fruitless.

Then, in the autumn of 1969, the scientific world was shaken by news from an international conference in Budapest. Professor McCusker, head of a cosmic ray research centre in Australia, announced the discovery of quarks!

He had placed a Wilson chamber at the centre of extensive atmospheric showers — dense streams of particles — created by protons of monstrous energy, reaching 10^{19} – 10^{20} electron volts, arriving from the depths of space. And it was precisely here that McCusker believed he had found these hypothetical particles. Among the 60,000 particle tracks photographed in the Wilson chamber, five appeared to be *twice* as faint. This seemed to correspond to ionisation reduced by half — the very signature quarks with a charge of 2/3 that of the electron were expected to leave.

And here is something interesting. Soviet theoretical physicists Ya. Zeldovich, L. Okun, and S. Pikelner attempted to calculate how many slowed-down quarks might exist on Earth. Their estimate yielded an incredibly small number

— quarks were found to be 10^{10}-10^{13} times less abundant than nucleons.

As Corresponding Member of the USSR Academy of Sciences E. Feinberg admitted:

> “This at least lifts some weight off our minds — it makes sense why they haven’t been observed so far, even if quarks are real.”

In the spring of 1971, a new report on the observation of fractional charge appeared in scientific journals. A niobium sphere, cooled to the temperature of liquid helium, was suspended in a vacuum along the magnetic field lines between the plates of a capacitor. The sphere was alternately bombarded with positive and negative electrons from radioactive sources, which were automatically brought close to it.

After this process, the sphere’s charge — expected to be a multiple of the elementary charge — should have been fully neutralised. However, when a high-frequency field was applied to the capacitor plates, the sphere behaved as if it possessed a fractional charge equal to 1/3 of the electron’s charge.

Does this mean that quarks were finally discovered?

It is difficult to say. This experiment, like McCusker’s results, lacks definitive proof.

> “It seems reasonable to assert that no such particles exist with masses below 6–8 GeV (i.e., 6–8 times heavier than nucleons),”

wrote Academician Ya. Zeldovich.

> "Alternatively, they may not be that heavy (for instance, a quark's mass might be approximately 2.5 times that of a proton), but they interact strongly with pi-mesons and therefore... in the competition between different processes, they give way to pions,"

suggested Corresponding Member of the USSR Academy of Sciences E. Feinberg.

> "It is doubtful that quarks exist in a free state. Just as sound cannot exist in a vacuum, quarks too may not exist freely, although they might play an important role in the structure of elementary particles,"

said Corresponding Member of the USSR Academy of Sciences D. Blokhintsev.

Six months after the creation of the quark model, its author, American scientist M. Gell-Mann, arrived in Dubna for the International Conference on High Energy Physics. When asked, "Do quarks exist?" he responded briefly: "Who knows?"

> "I fear that a different pen — a writer's pen — would be needed to convey all that he put into those two short words. In them, one could hear a profound respect for experiment, which ultimately determines and advances science; there was also M. Gell-Mann's characteristic intellectual boldness, his sense of

> discovery, his readiness to accept whatever nature reveals and to build a new theory from it, inspiring new experiments,"

wrote Academician Ya. Zeldovich in his reflection on Gell-Mann's response.

The "Quark Chorus"

Optimists still hope for the discovery of quarks, arguing their belief with reasoning such as: "The search for the neutrino and the antiproton took a quarter of a century, while the entire history of quarks is not even ten years old. Let's see what the future holds."

Well, these words are not without merit. Some scientists believe that if quarks could not be found in Serpukhov, they should be sought at the accelerator in Batavia, where protons are accelerated to an energy of 400 GeV. And if that too fails, the search should be postponed until an even more powerful machine is built.

These scientists should not be reproached for their persistence. Their determination has solid grounds. The discovery of quarks would fundamentally change our understanding of the nature of matter. Moreover, the classification of fundamental particles, which follows so naturally from the quark model, would gain strong support.

Optimists already have some facts in their favour. It has been observed that high-energy particle collisions often behave as if they are interactions between quark pairs

within those particles.

Meanwhile, a pessimist's intuition suggests: "Quarks do not exist, and that is why they have not been found."

Of course, everyone has their own opinion, especially since free quarks have indeed not been discovered. It may well turn out that they never will be. A large group of scientists holds this view. However, when it comes to assessing the meaning of the quark model itself and the entire "Eightfold Way," the opinions of optimists and pessimists converge.

The well-known theorist V. Weisskopf, himself sceptical about quarks and doubtful of their existence, once shared an anecdote about Niels Bohr in a conversation with journalists.

While visiting a friend's house, Bohr noticed a horseshoe nailed above the door and asked what it meant.

> "It brings good luck, he was told."
> "Do you really believe in that? Bohr asked."
> "Oh, I don't believe in it, but I must tell you — it works even if you don't believe."

And quarks, whether we believe in them or not, also "work." Eight years ago, Murray Gell-Mann introduced them to the world. Since then, quarks have endured indifference and scepticism, bursts of intense interest, and the disappointment of experimentalists. Finally, they have found a stable and steady acceptance among theorists.

Last year, a book titled *The Theory of Quarks* sold rapidly in bookstores. Flipping through its pages, one would quickly find what they were looking for:

> "Over the past six years, the quark model has firmly established itself in physics, even though quarks themselves have not been discovered. The theory of quarks has secured its position, and alongside specialised articles dedicated to quarks, the model is used in virtually all books on elementary particles and features in reports and reviews at every high-energy physics conference."

It is difficult to make a more convincing statement about the "workability" of quarks than the one given by Professor D. Ivanenko in the introduction to the book. The question now comes down to one thing: *are quarks merely a vivid representation of the properties inherent in elemen-*

tary particles, or are they real particles?

Regardless of how this question is ultimately resolved, it is already clear that the quark model has proven to be fertile ground for the emergence of new theoretical ideas. It has contributed to attempts to explain the properties of light particles and to the development of astrophysical and cosmological theories.

"The quark model," writes Professor D. Ivanenko, "has firmly established itself as a 'chorus' without which the 'soloists' could not reasonably perform in the front ranks."

Instant Photograph

While theorists were debating the problem of quarks, experimentalists had a remarkable surprise in store for them. At Stanford University, a new electron accelerator was launched with an energy of 17 billion electron volts.

With electrons accelerated to such levels, it became possible to attempt to peer into the depths of nucleons. Professor Panofsky conducted a special experiment, hoping to detect the constituent parts of the proton — if they indeed existed. The idea for this experiment was inspired by the quark model.

Leaving theorists to sharpen their theoretical tools in verbal duels at international conferences and meetings, experimentalists decided to finally take the bull by the horns. If quarks could neither be created nor detected in

macroscopic objects, could they at least be found within nucleons? But how best to do it?

In R. Hofstadter's early experiments on determining the size of nucleons, the wavelength of the probing electrons was so large that it was impossible to discern fine details – only the general contours of the nucleons could be perceived. It was similar to how farsighted people struggle to see details of objects placed too close to their eyes. Therefore, for this new task, only very high-energy electrons with short wavelengths were suitable.

Now, the key question was *how these electrons would scatter after transferring a significant portion of their energy to the proton*. This was no simple task. It was necessary not only to detect an electron flying at a specific angle but also to measure its energy.

Once all the technical difficulties were overcome, sci-

entists were left with long sequences of numbers — overwhelming to a non-specialist but a remarkable result of a complex experiment. However, it would be a mistake to think that a physicist could simply glance at these numbers and exclaim, "Eureka!" Everyone was eager to know: What had the fast electrons found inside nucleons? How had they transferred their energy — entirely to a single proton or to some of its internal components?

Before answering these questions, every possible experimental error had to be accounted for, and the final stage — mathematical analysis of the results — had to be carried out. And that was when the numbers *began to speak*, and how!

"The proton is not like a jelly-filled sphere but more like raspberry jam with seeds," remarked one of the theorists interpreting Panofsky's results. The scattering of electrons suggested that the proton was composed of point-like particles.

The renowned American theoretical physicist Richard Feynman coined the term *partons* for these entities. The word comes from the English part, meaning "component" or "constituent." This seemingly simple concept contains just as profound an abyss of the unknown as the enigmatic quark.

At the 1969 International Rochester Conference in Kyiv, physicists heard about partons for the first time. Many immediately wondered: *Can partons be identified with quarks?*

Unfortunately, there is no clear answer to this question. The nature of partons remains uncertain. Some speculate that partons are pi- or K-mesons. Others believe that partons are similar to quarks. Indeed, if partons are assigned a fractional electric charge, theoretical calculations align well with experimental data.

Yet, the existence of quarks cannot be considered proven. The scattering of high-energy electrons on nucleons provides, as Feynman puts it, only a "snapshot" of point-like constituent particles inside the nucleon. But from this, one cannot determine what they should look like in a free state or what properties they must possess.

A well-known example is the neutron, which exhibits different properties depending on where it is found — whether in free space or within an atomic nucleus. The nucleus remains stable, while a free neutron is unstable. Within less than fifteen minutes, it decays into a proton, an electron, and a neutrino.

Similarly, a quark with a fractional charge and large mass would likely undergo a transformation if ever found in a free state. After all, is a shriveled piece of rubber anything like a fully inflated balloon?

What partons might turn out to be if examined in greater detail remains unknown. And here, a vast field for theoretical imagination opens up!

4 Lost Illusions

> He walked amid the boundless dark
> Following a falling star,
> Through the uncertainty of quantum
> Mechanics yet to come.
>
> And when the next curtain
> Suddenly was drawn aside,
> He took a different limit and
> Rearranged the chess pieces anew.
>
> *P. Antokolsky*

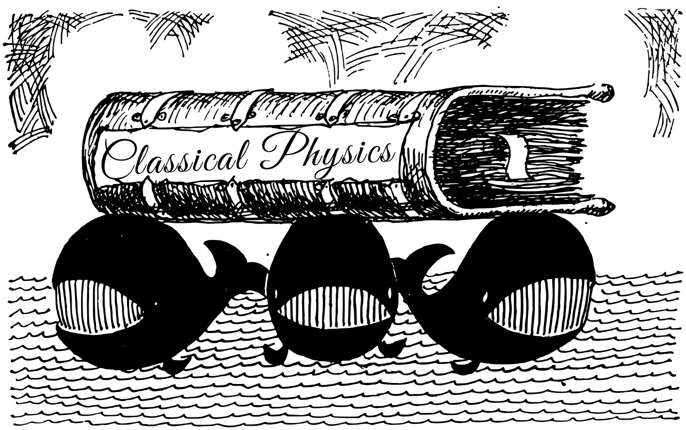
The Theta–Tau Puzzle

The dazzling fireworks of elementary particles soon ceased to amaze their discoverers. The registration of each new resonance — now numbering over a hundred — evoked in researchers the same emotions a nurse feels when looking at a long queue of patients.

If the goal and purpose of microphysics were merely to issue “passports” for an endless stream of new particles, there would be little left to discuss.

“The mastery of Earth by humanity is directly linked to the expansion of knowledge about the laws of nature,” wrote physicist and Nobel laureate Eugene Wigner. Thus, the purpose of science is not merely to discover and describe natural phenomena and processes. The primary objective is to uncover the fundamental relationships between them.

Several centuries ago, three fundamental laws of mechanics were discovered and studied: the law of conservation of energy, the law of conservation of momentum, and the law of conservation of angular momentum. These three conservation laws form the foundation of classical physics.



Upon discovering the atomic nucleus and elementary particles, scientists entered a new realm of nature. Here, for the first time, the limitations of certain macroscopic laws became apparent. In the microworld, its own quantum laws governed interactions. Atoms and elementary particles also obeyed the three great conservation laws, but instead of being described by Newtonian mechanics, they followed the principles of quantum mechanics.

Until the early 20th century, physicists were unaware of the direct connection between the three conservation laws and fundamental properties of space and time — such as their uniformity and the isotropy of physical laws, meaning that they remain the same in all directions.

Ohm's Law for electrical circuits holds just as well in a school in Moscow as it does thousands of kilometres away in a school in India. But why does this, like any other law of nature, work just as well today as it did yesterday, and why can we be confident it will remain unchanged tomorrow? The reason lies in the homogeneity of space and time — their properties are the same everywhere and at all times.

We rarely think about this fact, as it seems irrelevant to our daily lives. However, the very existence of natural laws depends directly on the homogeneity and symmetry of space and time.

The word "symmetry" usually brings to mind images of geometrically symmetrical objects. However, in a broader sense, symmetry is associated with the unity of two opposing aspects — *preservation* and *transformation*. Symmetry

means the conservation of certain elements with respect to specific changes.

After the development of relativity and quantum mechanics, it was unexpectedly discovered that all three conservation laws governing both the macroscopic and microscopic worlds were merely consequences of more fundamental principles — the symmetry principles of space and time! Since then, these fundamental principles have occupied the highest tier in the hierarchy of physical concepts.

At first, physicists had no doubts about the validity of these principles. However, like a bolt from the blue, the "theta-tau" puzzle emerged, as it came to be recorded in the annals of physics. The essence of this mystery boiled down to a single question: *was it one particle or two?*

The culprits of this puzzle were the heavy kaons (K-mesons). From the moment of their discovery, kaons attracted intense attention from physicists and quickly earned the nickname "strange" due to their peculiar behaviour: *they were produced through strong interactions yet decayed via weak interactions*. In the brief moments when kaons were observable, scientists learned as many astonishing facts about them as an inquisitive journalist might uncover about a famous movie star over many months.

It was soon revealed that the term "kaon" actually encompassed three distinct types of elementary particles. Some were neutral — K^0-mesons — while others carried an electric charge: K^+-mesons were positively charged,

and K^--mesons were negatively charged.

The first intriguing case involved K^+-mesons. Typically, they decayed into lighter particles through multiple pathways, which in itself was not surprising. What was puzzling, however, was this: according to theoretical models, two of these decay modes appeared as if they belonged not to a single particle but to two different ones. The temptation to attribute both decay modes to a single particle was hindered by a fundamental constraint — another general law known as the *law of conservation of spatial parity*.

Parity is a mathematical concept that is difficult to explain solely through physical intuition. It is a property of the special wave function that describes the state of an elementary particle in quantum mechanics. The law of conservation of spatial parity states that this parameter should remain unchanged.

To a non-specialist, these words may mean little. However, the term *spatial* in "spatial parity" already hints that this law arises in quantum mechanics as a direct consequence of the invariance of space under mirror reflection.

Physicists had long known that mirroring spatial coordinates — swapping positive and negative signs and exchanging left and right — had no effect on the microscopic world. Real processes in the microcosm exhibited spatial symmetry, also known as P-symmetry. It seemed firmly established that nature made no distinction between "left" and "right."

However, new types of K^+-meson decays were discovered, forcing physicists to reconsider. If the same particle, under identical conditions, could decay in ways that suggested its parity had changed, then the logical conclusion was that the law of spatial parity conservation had been violated. But the mere thought of such a violation — linked to the principle of mirror symmetry, which itself followed from the homogeneity of space — was unsettling, even terrifying!

Physicists thus decided to assume that there were not one but two types of K^+-mesons, each decaying in different ways due to opposite parity. They named them theta-mesons and tau-mesons.

It seemed the issue was resolved, but this brought no peace to either theorists or experimentalists. Scientists were accustomed to probing the very essence of things, leaving no ambiguities or unresolved questions. Yet here, both remained.

No one could understand why tau- and theta-mesons, which were experimentally indistinguishable and had the same mass and lifetime, decayed differently. Could it be that they were, in fact, the same particle? But accepting this meant abandoning the belief in the inviolability of fundamental symmetry principles.

"The situation physicists found themselves in at the time," recalled one scientist, "was like that of a person groping for an exit in a dark room; he knows there must be a door leading outside, but in which direction?"

The way "outside" was found only in 1956. The first to "discover the door" were American physicists Tsung-Dao Lee and Chen-Ning Yang. However, they seemed to have stepped through it in the most unexpected way. They "erased" the terms "theta" and "tau" and declared that only one type of K-meson existed — with a positive electric charge.

This was an extraordinarily bold claim. The two American physicists had cast doubt on the previously unquestioned law of spatial parity conservation. Their radical hypothesis proclaimed that in K-meson decay under weak interactions, mirror symmetry of space was violated!

Did this mean that space was not homogeneous? It was almost impossible to believe. After all, all other experiments had strictly confirmed the law of parity conservation — both in atomic phenomena and in strong interactions between particles!

Lee and Yang were the first to realise that all previous tests of mirror symmetry "might be worthless in this unexplored realm of vanishingly weak interactions."

The discovery of weak interaction — one hundred billion times weaker than electromagnetism — had already been accompanied by temporary doubts about the validity of the law of energy conservation. Remember the circumstances under which the neutrino was proposed and discovered? Now, weak interaction was challenging yet another fundamental principle of nature.

The renowned theoretical physicist Freeman Dyson recalled reading Yang and Lee's manuscript twice and saying,

> "This is very interesting," or something to that effect. "But I lacked the imagination to exclaim: 'My God, if this is true, it opens an entirely new domain in physics!' And I think that, with very few exceptions, all other physicists at the time were just as unimaginative about it as I was."

Even a hypothesis that faces no objections, one that seems to be "in the air," does not gain acceptance until it is confirmed experimentally. And this idea, which was met with outright resistance, had an even higher bar to clear.

Everything now depended on an experiment that would directly test the mirror symmetry of space.

Journey Into the Looking Glass

Many people believe that they see their exact double in a mirror. But if they look more closely, they will notice just how different the reflection is from the original. The mirrored image has the right corner of its mouth lifted instead of the left, and even its nose points in the opposite direction. Left and right have *swapped places*: the heart of the person in the Looking Glass world is on the right, while the spleen is on the left.

A human being is an asymmetrical object. They do not possess spatial symmetry, and therefore will never encounter an identical double in the mythical land of the

Looking Glass.

In the world of elementary particles, however, physicists once believed that all processes mirrored their counterparts *exactly*.

Now, after the hypothesis of Lee and Yang, a *direct comparison* had to be made between the process of radioactive beta decay of nuclei (the original) and its mirrored image. The decay of K^+-mesons was unsuitable for such a test due to their extremely short lifespan — 10^{-10} seconds.

Studying K-mesons required an extremely powerful accelerator and massive instruments for recording nuclear processes. It was with the help of this impressive technology that the famous "theta-tau" mystery arose.

The solution to this puzzle was found in a simple and highly refined laboratory experiment — what physicists

call a “tabletop” experiment, conducted far from any accelerator. The chosen subject was a radioactive isotope of the chemical element cobalt, well known for lending its name to a medical device — the cobalt gun.

It has long been known that, as a result of weak interactions in cobalt nuclei during beta decay, neutrons spontaneously transform into protons, while electrons and neutrinos are emitted from the nucleus. Following them, gamma quanta — those same quanta used in medical treatments — are also released. The emitted electrons predominantly travel along the axis of the nucleus’s magnetic moment.

Until 1956, all physicists believed that both directions along this axis — the forward and the reverse — were equivalent, as space itself was considered homogeneous. They assumed that for every electron emitted to the right, an *equal number* would be emitted to the left. In other words, the beta decay process of cobalt nuclei was thought to be *mirror-symmetric*.

However, after experiments with *K*-mesons, doubts arose about this assumption. Everything needed to be tested experimentally. But such an experiment could only be conducted if all cobalt nuclei could be aligned in such a way that their magnetic moments matched the direction of an external magnetic field created by a coil. Then, it would be possible to compare the number of electrons detected when the external field was oriented in one direction with the number detected when the field was reversed.

This would essentially serve as a test of whether the

beta decay of cobalt truly exhibited mirror symmetry.

But atomic nuclei are not bowling pins that can be easily arranged.

Is there another way to orient nuclei? One scientist aptly remarked that the only "handle" by which an atomic nucleus can be turned is its magnetic moment. However, this handle is so tightly coupled with the magnetic moment of the entire atom that it can only be turned by rotating the entire atom.

The preparation for unraveling the "theta-tau" mystery lasted six months. In a special cryostat, cobalt atoms were frozen to just one degree above absolute zero. At such low temperatures, thermal motion could no longer interfere with the external magnetic field's ability to dictate the atomic "parade."

This experiment was led by the American scientist Dr. Chien-Shiung Wu of Columbia University.

> "I remember," recalled F. Dyson, "how in October 1956, I met Yang and said to him, 'It would be great if Wu's experiment yielded something.'
> 'Yes,' he replied, 'that would be great,' and then continued telling me about his calculations in the theory of non-ideal gases. I think even he didn't fully realise at the time just how great it would be."

Wu's experiment, which took six months to prepare, lasted only fifteen minutes. As soon as the apparatus was switched on, physicists immediately understood that the

principle of mirror symmetry in weak interactions was *violated*. Significantly *more* electrons were emitted against the direction of the magnetic field than along it.

The journey into the *Looking Glass* never happened! Unheard of! The weak interaction *distinguished* between right and left directions. The experimentally observed preferential emission of electrons in one direction, just like the asymmetries in the human body, ruled out the existence of a mirror twin for the beta decay process of atomic nuclei. Indeed, in an ordinary mirror — let us call it the "*P*-mirror" — beta decay appeared differently: there, *electrons were emitted primarily in the direction of the nucleus's magnetic moment*. But no such process exists in nature.

It is hard to describe the excitement among physicists. Theorists struggled to grasp the implications of the result, while experimentalists set out to examine other weak interaction processes that had not yet been tested for adherence to mirror symmetry. There was still a flicker of hope that the heretical result of the beta decay experiment would not be confirmed in other phenomena.

But every measurement led to the same conclusion:

> *the principle of mirror symmetry remained unshaken in strong interactions, but it failed in weak interactions.*

For the first time, atomic physics revealed the limited applicability of certain Newtonian mechanics conservation laws. And now, in the world of elementary particles, the

fundamental principle of spatial symmetry was found to be *neither universal nor absolute*.

What, then, must we now imagine our space to be?

Could it be that its perfect uniformity and symmetry are illusions? And how does this reconcile with the fact that all processes in the world of elementary particles obey the law of conservation of momentum — a law that itself arises from the uniformity of space?

The First "Victims"

Lee and Yang were right. In nature, there existed only one type of K^+-mesons, whose decay sometimes violated the law of spatial parity conservation. The principle of mirror P-symmetry was broken in weak interactions. Just like other non-mirror-symmetric phenomena, the weak interaction was forbidden entry into the *Looking Glass* world.

But before physicists could recover from the shock and process the emerging questions, another revelation struck them.

Experimenters discovered that the positron radioactive decay of another cobalt isotope, in which the nucleus emitted the electron's antiparticle — the positron — did not occur in the same way as electron emission: *positrons were ejected in the opposite direction*.

This new finding made an impression on scientists no less profound than the first. But why were they so shaken?

Why, after all, should positron decay behave exactly like electron decay?

How could they not be unsettled, when one of the fundamental principles of elementary particle physics — the principle of charge symmetry, or *C*-symmetry (from the English word *charge*) — insisted on their *complete equivalence*?

> "About forty years ago," wrote L. Okun, "the idea of charge *C*-symmetry in physics equations seemed strange even to the founders of quantum mechanics. However, the entire structure of the fundamental equations demanded such symmetry, and subsequent experimental discoveries of antiparticles brilliantly confirmed it."

> "Theory proclaims that analogous processes involving particles and antiparticles occur in the same way."

But theory is one thing, and practice — where electrons and positrons behave differently in similar radioactive decays — is another. It turned out that weak interactions not only lacked mirror symmetry but also charge symmetry!

"But how could a principle be elevated to a fundamental law without being experimentally verified?" a curious reader might ask.

Yes, that is exactly the point — it *had* been tested, and not just once, but never in the context of weak interactions. This paradox, which had long remained successfully

hidden from physicists, only surfaced in experiments involving processes governed by weak interactions.

If the violation of mirror symmetry seemed to be related to the peculiar properties of space itself, with particles playing no direct role, then the violation of charge symmetry touched upon the very nature of matter. After all, the electron is a fundamental building block of ordinary matter, while the positron is a fundamental building block of antimatter. These experiments immediately raised two immense questions. One concerned the nature of space, while the other appeared to relate to the differences between particles and antiparticles. Without resolving these issues, progress was impossible.

And yet, after some time, physicists managed to untangle this incredibly complex knot of problems. Imagine an unusual kind of mirror, which we will call a *charge mirror*, or *C*-mirror, in which particles appear as their corresponding antiparticles. In this mirror, electrons emitted during the radioactive decay of a nucleus do not appear as "mirror electrons," but as positrons flying in the same direction as the original electrons. However, the resulting reflected image — the mirror version of the real process — remains *lifeless*, in the sense that it does not resemble any actual process that occurs in nature. This means that the *C*-mirror does not work in weak interactions either.

But wait — haven't we seen something similar before, when dealing with the ordinary *P*-mirror? In that case, the image suffered from a different flaw: electrons remained

electrons, but they were emitted in the "wrong" direction. What if we were to use both of these flawed mirrors simultaneously and observe how our process would appear then?

It turns out that in this *CP*-mirror, electrons become positrons and are emitted in a direction that would be "incorrect" for electrons but perfectly valid for positrons. And that is precisely what we need. The reflection in the *CP*-mirror now represents a physically meaningful process — one that is identical to the actual positron-emitting nuclear beta decay.

This concept of a combined *CP*-mirror was first proposed by the eminent Soviet theoretical physicist and Nobel laureate Lev Landau. The *CP*-mirror *simultaneously* inverts spatial coordinates and transforms particles into their antiparticles. After rigorous experimental verification, physicists found that this symmetry transformation held true in all interactions, including those governed by the weak force.

What was the outcome? Previously, both parity (*P*) symmetry and charge conjugation (*C*) symmetry were considered fundamental principles of nature. However, once experiments demonstrated that each was violated individually, physicists were forced to abandon them as universal laws and instead establish a new principle — *CP* symmetry, which appeared to hold across *all* types of interactions, including the weak interaction.

Processes governed by the strong interaction, which

remain invariant under both spatial reflection and charge conjugation, naturally obey *CP* symmetry.

However, for weak interactions, the new principle implied that every such process involved not only a spatial reflection but also the transformation of particles into their antiparticles. As Pushkin wrote: "If he turns right, he starts a song; if he turns left, he tells a tale." Nature, it seemed, demanded that in weak interactions, a shift from right to left was always accompanied by a transition from matter to anti-matter.

Right and left turned out to be intrinsically linked to matter and antimatter; the distinction between these directions corresponded to the difference between particles and antiparticles. This was the physicists' answer to the two profound questions that arose from solving the *theta-tau* puzzle. Empty space, when reflected in both an ordinary mirror and a *CP*-mirror, remains symmetric and homogeneous. If weak interactions appear to violate mirror symmetry, the cause lies not in space itself but in the properties of the particles involved.

This discovery provided a concrete new confirmation of a fundamental tenet of dialectical materialism: *the unity of space and matter*.

It is worth recalling that scientists first noticed the connection between the geometric — spatial — properties of matter and its physical properties in the mid-19th century. This issue initially emerged in crystallography, where leading researchers were puzzled by a well-established

experimental fact: some chemically identical substances exhibited different optical properties. Why was this the case?

"As those who pondered this question wrestled with their doubts," wrote the renowned crystallographer Charles Bunn in his book *Crystals: Their Role in Nature and Science*, "they experienced the kind of intellectual discomfort that often drives new discoveries."

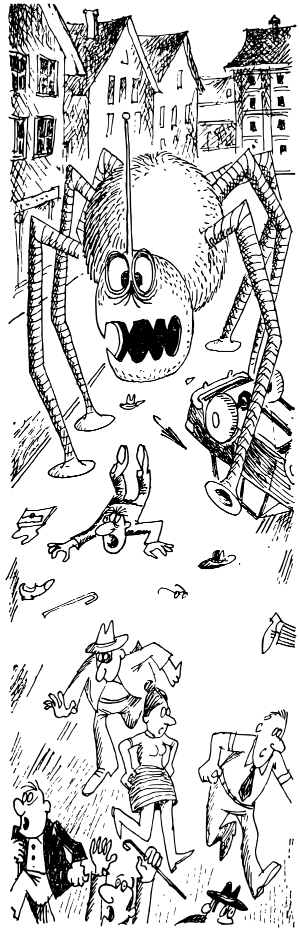
A young Louis Pasteur became intrigued by this problem. "I could not accept the idea," he wrote, "that two substances could be so similar and yet not be completely identical. Shortly after finishing my studies at the École Normale Supérieure, I decided to grow more crystals to study their form." Before long, Pasteur discovered that these chemically identical substances consisted of crystals that were oriented differently in space.

These crystals turned out to be mirror images of each other. They did not coincide and exhibited different optical activity. "The discovery of right- and left-handed tartaric acids (which was Pasteur's achievement) helped move molecules out of the realm of vague speculation into the concrete world of geometry," wrote Charles Bunn.

What is most significant for us in this history is that it marked the first time science revealed a dependence of matter's properties on its spatial orientation.

A century later, this issue reemerged — not in macroscopic physics but in the realm of elementary particles.

However, the new problem was far more complex, as it involved not only particles but also antiparticles.



Just as Pasteur identified a connection between the properties of right- and left-handed substances (left- and right-handed crystals), the world of elementary particles provided a unique opportunity to uncover a relationship between the properties of right-handed matter and left-handed antimatter.

Astrophysicists are now searching for antimatter worlds in interstellar space by studying different types of cosmic radiation. Meanwhile, science fiction writers imagine their protagonists encountering visitors from a mysterious antimatter universe.

It remains unknown whether a complete antimatter universe, fully analogous to our own, exists. However, weak interactions, through violations of spatial and charge symmetry, have already linked the fundamental building blocks of matter and antimatter. The analogy between the principle of *CP* symmetry and the combined "*CP*-mirror" is evident. But what kind of mirror is this? It resembles more of a "window into the antimatter world."

If one looks into this mirror alongside a neutrino, one sees an antineutrino — a particle with no mass and no electric charge, possessing only intrinsic angular momentum associated with its spin. However, in the mirror, the neutrino's spin direction is immediately reversed, making it identical to that of an antineutrino. Like an enchanted figure that can never see its own reflection, the neutrino

cannot "see" itself in the mirror.

And what about the electron? What does it see in the "*CP*-mirror" as it emerges from a radioactive nucleus? The electron sees its antiparticle — the positron.

Kaon Cocktails

In August 1964, scientists from numerous laboratories and research institutes around the world gathered in Dubna, near Moscow, home to the Joint Institute for Nuclear Research (JINR), for the traditional International Conference on High-Energy Physics.

Physicists eagerly anticipate these meetings, where theorists and experimentalists come together to discuss their latest findings. These conferences provide a rare opportunity to exchange ideas with colleagues from different countries and learn about the most recent, unpublished breakthroughs in the field.

Some attendees were eager to meet Murray Gell-Mann, the creator of quark theory, who was celebrating the triumph of the "eightfold way" following the recent discovery of the omega-minus hyperon. Others were hoping to hear the latest updates on neutrino experiments.

However, what captured everyone's attention were the rumours surrounding an upcoming announcement from scientists at Princeton University. Sensational claims are often exaggerated, but this time, both journalists and experts

found their expectations justified.

At first, there was no indication of any groundbreaking revelation. The years following the discovery of parity violation had only reinforced the validity of the emerging concepts about the nature of space, matter, and antimatter.

Physicists welcomed the year 1964 in a seemingly stable and well-ordered scientific environment. No one expected that, in the midst of the carefully cultivated "garden" of experimental results, an unexpected and thorny new complication would arise — the violation of CP symmetry.

The announcement by American scientists regarding a new experiment with neutral *K*-mesons had a profound impact. Once again, these "strange" particles challenged the very foundations of modern quantum theory.

Alexander Baldin, director of the High Energy Laboratory at JINR and corresponding member of the USSR Academy of Sciences, remarked that the American experiment "provided the maximum amount of information because it fundamentally altered our understanding. The observed effect was so incompatible with the existing theoretical framework that it remains the most significant discovery in physics in recent years."

But what exactly did scientists uncover? Before delving into their findings, we must first acquaint ourselves with neutral *K*-mesons — some of the most extraordinary entities in the microscopic world, true chameleons of the realm of elementary particles.

If we place a detector sensitive only to these particles at the exit of an accelerator and run measurements for a few hours, we would find that K^0 mesons have an extremely short lifetime of just 10^{-10} seconds before decaying into two pi-mesons.

Now, let us move the detector twenty metres farther away. What should this detector register? Logically, it should detect nothing! Given the minuscule lifetime of K^0 mesons, even if they were moving at the speed of light, they would only travel a few centimetres before inevitably decaying into two pi-mesons.

Yet, at twenty metres from the accelerator, the detector continues to register neutral mesons. These mesons have a lifetime 600 times longer, allowing them to reach the detector. Moreover, these long-lived mesons decay not into two, but into three pi-mesons. This suggests that the particle beam produced in high-energy proton collisions with a target consists of two distinct types of neutral K-mesons.

But that is not all. If an experimenter accidentally leaves an object in front of the detector counting long-lived K-mesons, a remarkable phenomenon occurs: *the detector suddenly starts registering short-lived K-mesons once again*. These mesons, just like those detected at the accelerator's exit, decay into two pi-mesons!

This "miracle" has a straightforward explanation. When long-lived mesons collide with matter, they transform into short-lived mesons. No other known particle exhibits

this behaviour. Neutrons, protons, and pi-mesons never change their fundamental properties upon interacting with matter.

In the table of elementary particles, each resident of the microworld occupies at most two rows. The first row belongs to the particle, and the second to the antiparticle. However, neutral K-mesons have managed to claim *four* rows!

The first row, as expected, is occupied by the neutral K^0-meson, while the second belongs to the anti-K^0-meson. The third position is taken by the already familiar short-lived K^0-meson, and finally, the fourth is occupied by the long-lived K^0-meson.

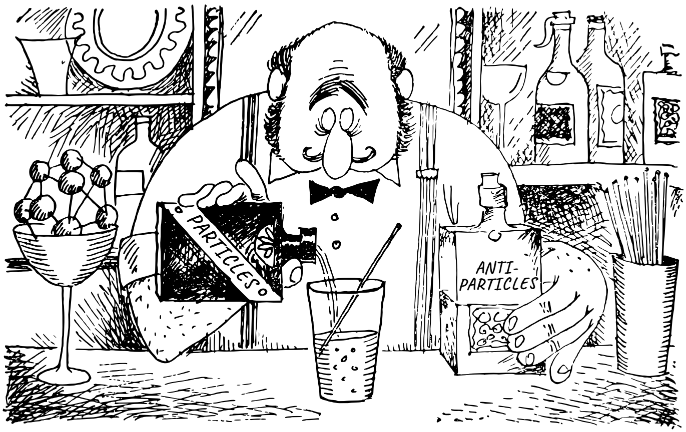
Despite numerous efforts, experimenters could not find an anti-K^0-meson in nature. This was not surprising — photons do not have anti-particles, nor does the neutral pi-meson. According to theory, these particles should be completely identical to their "anti-relatives."

However, when M. Gell-Mann developed his classification of elementary particles, his model implied that K^0-mesons should indeed differ from anti-K^0-mesons. The perceptive E. Fermi immediately asked him: "How can you consider K^0- and anti-$K^0$to be different if they decay in indistinguishable ways?"

"As is now clear," wrote B. Pontecorvo in his memoirs, "these words concealed a profound intuition about the dual nature of neutral kaons." (Physicists refer to K^0 mesons

simply as kaons.)

Encounters between particles and their antiparticles are extremely rare. Only a tiny fraction of protons or electrons ever meet their antiparticle counterparts. This is because matter and antimatter are always spatially separated. Only at the moment of their first (and final) meeting do some particles and antiparticles form a short-lived bound system. For example, an electron and a positron, before annihilating, can temporarily exist as a positronium atom — helping scientists solve certain chemical problems.



However, anti-K^0 mesons were nowhere to be found — neither in cosmic rays nor among the particles produced in accelerators. But they *had* to exist! — the theory insisted. One experiment followed another, and the persistent search continued. It continued until physicists finally realised that there was nothing to search for. The answer

was both simple and fantastically extraordinary.

Weak interactions had, in a way, *bridged* the world and the antiworld. They linked the violation of spatial mirror symmetry to the difference between particles and antiparticles — for example, in the sign of electric charge. In neutral *K*-mesons, matter and antimatter coexist side by side until their decay. They are nothing other than a *mixture* of particles and antiparticles. And not just one mixture, but two — two strictly coordinated, balanced states with well-defined mass, fixed lifetimes, and other quantum properties. Scientists named one of these mixtures the *short-lived neutral K-meson* and the other the *long-lived neutral K-meson*.

These very *cocktails*, carefully prepared by nature from two identical components, demonstrated their disagreement with the principle of *CP*-symmetry.

A One-Actor Theatre

What was so sensational about the announcement made in Dubna at the International Conference?

At Princeton University, American physicists Christenson, Cronin, Fitch, and Turlay were studying the properties of long-lived *K*-mesons produced in an accelerator. They positioned their setup twenty metres from the exit of the meson beamline to completely eliminate all short-lived *K*-mesons, which decay rapidly.

During their experiments, the physicists noticed something remarkable: very rarely — once in 500 usual decays — long-lived kaons violated the prohibition imposed by the principle of *CP* symmetry and decayed into two pi-mesons. According to theoretical laws, they should not have been able to do this. Yet the American physicists observed precisely such decay events. Did this mean that the *CP* mirror was also failing?

Once again, the asymmetry between right and left surfaced — an asymmetry that could *no* longer be explained by differences between particles and antiparticles.

Scientists reacted to this discovery in different ways. Skeptics argued that the anomaly must have been due to an error in measurements or data processing. Others pointed out that the experiment had not been conducted in a vacuum but in air, and that in the final stage, the mesons even passed through a helium-filled chamber. Any interaction with matter is critical for a neutral kaon: upon colliding with a substance, kaonic cocktails get shaken so violently that the long-lived mixture of particles and antiparticles transforms into a short-lived one, which then legitimately decays into two pi-mesons.

The accusation was serious, and a thorough verification process began. The Princeton experimenters conducted a special control test, which demonstrated that such transformations of long-lived *K*-mesons occurred 10^6 times less frequently than the previously recorded forbidden decays.

A little more time passed, and measurements conducted by different research groups using completely different experimental methods confirmed this fact. The last remaining skeptics were forced to accept the reliability of the discovered phenomenon.

This strange discovery once again brought scientists back to square one, to the unresolved question of why homogeneous space does not exhibit mirror symmetry in weak interactions. Action was needed. Like detectives solving a crime, scientists began searching for other *inhabitants* of the microworld that behaved similarly to neutral K-mesons.

A meticulous investigation was carried out into the decays of hyperons and mesons, nuclear decays, and nuclear reactions. However, nowhere, in any phenomenon, was a violation of CP symmetry found. The neutral K-mesons acted alone.

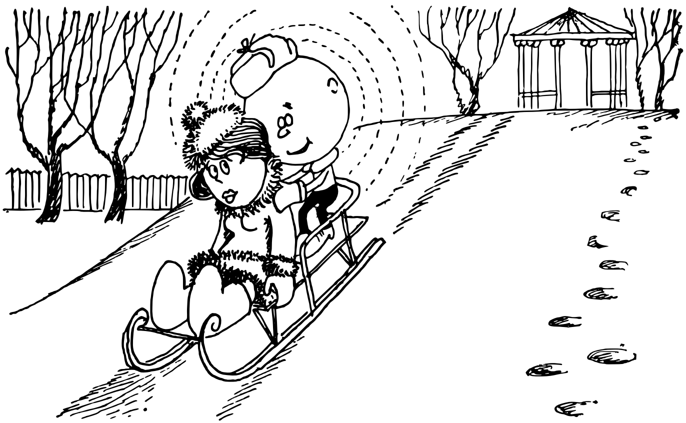
In this regard, the situation differed sharply from that of the discovery of mirror symmetry violation. Back then, experiments with positively charged K-mesons had served as a signal, lifting the curtain to reveal a large group of *conspirators* against the law of parity conservation — namely, processes occurring under weak interactions of elementary particles.

But now, behind the curtain, there was only a single actor — the long-lived neutral K-meson, defying the director's instructions of CP symmetry. If weak interactions were responsible, it was only for the *preparation* of the K-

meson *cocktails* — mixtures of particles and antiparticles.

How should we interpret the individuality of this lone *citizen* of the microworld? Perhaps with humour? Maybe Academician I. Tamm was right in suggesting that the story of the long-lived K-meson resembles the well-known history of the neutrino and the law of energy conservation? And that, in the end, CP symmetry will remain unshaken?

But physicists are not laughing, and not for lack of a sense of humour. Time passes, yet the *illusionist's trick* — the K-meson's anomaly — remains unsolved. And it hints at much more.



Remember how unamusing it was for Chekhov's Nadya[14], who couldn't tell whether it was the wind whistling in her ears or her companion whispering words of love from the sled?

[14] The reference is to Anton Chekhov's short story *The Kiss* (1887). In the story, Nadya, a young woman, is uncertain whether the wind is whistling in her ears or if her suitor is whispering words of love. – DM

And what is the K^0-meson whispering to us?

Saving the fundamental principle of spatial symmetry, physicists initially blamed external long-range forces, which could originate from the Earth, the Sun, or the Galaxy. However, experiments contradicted this hypothesis, and it had to be abandoned.

Another idea is currently being tested. What if the unusual decay of the neutral kaon is caused by a hypothetical *super-weak interaction*?

One way or another, the question of why long-lived K-mesons decay into two pi-mesons remains one of the most fundamental questions in modern physics.

> "The essence of this phenomenon is unclear," says Corresponding Member of the USSR Academy of Sciences F. Shapiro. "But it represents such a radical shift in our understanding that, someday, I believe, it will have far-reaching consequences for the entire structure of physics."

Paradise Lost

The "strange" positively charged K-mesons were the first to sound the alarm for the fundamental principle of spatial symmetry. This threat was mitigated by accepting the "ultimatum" of weak interactions — replacing particles with antiparticles under mirror reflection.

The violation of either spatial or charge symmetry in

weak interactions was already unsettling for physicists. But the simultaneous violation of both *C*- and *P*-symmetries shook the very foundations of modern physics.

Every equation in quantum mechanics is symmetric not only with respect to changing the sign of all coordinates (*P*-symmetry) or replacing particles with antiparticles (*C*-symmetry) but also with respect to *reversing the direction of time* — what is known as "time reversal."

This temporal, or *T-symmetry*, suggests the "eternal youth" of processes in the microscopic world. *T*-symmetry implies the absence of the "arrow of time," as the macroscopic world's time direction is poetically described. In the realm of elementary particles, the concept of "aging" does not apply. There exist only two equally valid directions of a process — *forward and backward*.

This is important to recall because modern quantum field theory of elementary particles is based on the CPT theorem. Its essence is that all processes must simultaneously obey spatial (*P*-), charge (*C*-), and time (*T*-) symmetry. In other words, any phenomenon in the microscopic world, when reflected in a mirror, with particles replaced by antiparticles and the final state exchanged for the initial one (i.e., reversing the direction of time), should still correspond to a *physically real process* in nature.

Before the ka-meson experiments, no one doubted that all three types of symmetry — both individually and together — were strict laws of nature. But the first two have already lost their universality. What are the consequences?

If *CP*-symmetry is violated while *T*-symmetry remains intact, then the entire *CPT* theorem collapses. The only way for the general *CPT* symmetry to hold is if *CP*- and *T*-symmetries are violated simultaneously.

Thus, having lost two fundamental laws, physicists are "voluntarily" relinquishing the third. Moreover, they are actively seeking evidence of its violation in order to preserve the foundations of the theory. But does time hold power over the microworld?

Determining this is far more difficult than in the macroscopic world. Temporal *T*-symmetry imposes restrictions on certain physical phenomena. For example, elementary particles should not have an electric dipole moment. One can imagine a neutron as being composed of positive and negative charges with their centers of mass slightly separated, which would create an electric dipole moment. If nuclear processes are truly reversible, then the neutron's dipole moment must be precisely zero.

At the *Laboratory of Neutron Physics* in Dubna, scientists have long been searching for ways to uncover the secret of the electric dipole moment of particles. In all previous experiments, it has not been detected. However, it is still too early to conclude that the dipole moment is strictly zero — the experimental precision is not yet high enough. Neutrons pass through the working volume of the setup so quickly that only a very small fraction of them decay during that time. Even slow, or thermal, neutrons travel at a speed of two kilometers per second. The neutron "tor-

rent" crosses the entire apparatus in mere fractions of a second, whereas measuring the dipole moment requires the neutron to remain within the experimenters' field of observation for as long as possible. During this time, its behavior under the influence of electric and magnetic fields must be thoroughly studied.

Thus, there arose a need for neutrons much slower than thermal ones. Such ultracold neutrons, moving at a speed of a few meters per second, are found among the particles emitted from a nuclear reactor. However, they are extremely rare: *only one ultracold neutron per one hundred billion total neutrons*.

If only it were possible to collect and preserve these neutrons, then the experiment to measure the dipole moment could be conducted with high precision.

And this seemingly fantastic idea turned out to be practically feasible. About twenty years ago, the Italian scientist E. Fermi and the Soviet theoretical physicist I. Pomeranchuk demonstrated that ultracold neutrons should be completely reflected from the surface of certain substances.

Ten years later, Academician Ya. Zeldovich theoretically proved that by using this reflection property, it would be possible to “capture” ultracold neutrons from a reactor and accumulate them in a special trap — up to one hundred million neutrons per cubic meter!

It was hard to believe. After all, neutrons are highly penetrating particles, yet it was predicted that they would be unable to escape from a trap made of the thinnest copper foil.

The unusual behavior of ultracold neutrons was explained by their wave properties. The wavelength of these particles is one hundred-thousandth of a centimeter. But in the microworld, even that appears gigantic — like Gulliver among atomic Lilliputians. As a result, when the wave reaches the surface of a substance, it interacts simultaneously with a large number of atomic nuclei in the copper. Although the energy of this interaction is very small, it is still of the same order as the energy of the ultracold neutrons themselves. This is why even the first layers of atomic nuclei in the foil create an insurmountable energy barrier for the ultracold neutron waves. Like an ocean wave crashing against a steep shore, they are forced to roll back.

A group of scientists from the Laboratory of Neutron

Physics at the Joint Institute for Nuclear Research (JINR), led by F. Shapiro, has already begun creating "canned" neutrons. Their task was formulated quite simply: to find and extract needles — ultracold neutrons — from a haystack, that is, from among hundreds of billions of other neutrons.

The experimenters placed a copper tube in the neutron stream coming from the atomic reactor, bending it at the end farthest from the reactor. Thermal neutrons, moving at enormous speeds, passed through the tube walls at the bend and continued on their way. However, ultracold neutrons, once inside the tube, could no longer escape and became trapped. Like blind kittens, they bumped into the walls and, reflecting off them, crawled along the tube, following its curves.

The experimenters confirmed this by placing a detector at the bent end of the tube, which registered neutrons that had remained inside for about 200 seconds!

Once scientists learn to create "canned" neutrons in sufficient quantities, they will be able to measure the neutron's electric dipole moment with great precision.

In dozens of laboratories around the world, experiments are being conducted to test the violation of temporal symmetry. But so far, there is no definitive answer.

Let us speculate for a moment and imagine that the violation of *T*-symmetry has been confirmed. The *CPT* theorem would then be saved, but at what cost! Once again, we would face the puzzling asymmetry of left and right, the

non-equivalence of forward and reverse directions in time, and the non-equivalence of particles and antiparticles. We would have to accept that the microworld is "tainted" by the same asymmetries that we have long since become accustomed to in our macroscopic world.

In the world accessible to our senses, we constantly encounter objects that lack mirror symmetry. There is no need to look far for proof: *our own mirror reflection only resembles us*.

What are we and everything around us made of? Protons, neutrons, and electrons. And there is nothing and no one composed of antiprotons, antineutrons, and positrons. The charge asymmetry of the macroscopic world is evident.

As for time, there is no need to argue. Its relentless arrow always points forward.

> Never call anyone back.
> Reversibility is a lie,
> The essence of motion is malicious,
> Neither he nor she
> Will be returned to you.
> — *I. Snegova*

What, then, is the significance of this similarity revealed by high-energy physics, this matching asymmetry of our ordinary world and the world of the infinitesimally small? What is the connection between the violation of C-, P-, and T-symmetries in the macro- and microworlds? *Do*

the CPT symmetries of the microworld correspond to CPT symmetries of the macroworld?

Both of these questions, scientists say, lead the one asking them deep into cosmology. After all, the charge and temporal asymmetries of our surrounding world are consequences of the special "initial" conditions that existed in the universe approximately 10^{10} years ago.

The violation of spatial and mirror symmetries in weak interactions, the inadequacy of the "*CP*-mirror" for a small number of neutral kaon decays... Are these minuscule deviations really so important against the vast background of strong interactions, which obey *C*-, *P*-, and *CP*-symmetry? Against the backdrop of those very forces that bind nucleons in nuclei and govern the overwhelming majority of the tiniest building blocks of matter? And why, after all, do physicists so diligently study these small symmetry violations in the microworld?

> "Because," says Doctor of Physical and Mathematical Sciences D. Frank-Kamenetsky, "in science, there are no trivialities. It is obligated to explain everything to the very end, and every unexplained phenomenon may conceal an entire ocean of the unknown. A tiny black spot on a photographic plate lying next to a uranium sample turned out to be the precursor of all nuclear physics and technology."

Physicists have already formed the impression that the world is simple in its general outlines but extremely complex in its details. The most alarming symptom of com-

plexity is symmetry violation. After all, everything simple is symmetrical.

How these stories will ultimately reshape our understanding of the world remains unknown. This remark is equally true for the third mystery, which has yet to become history.

The new enigma, just recently discovered by physicists — "the $K_2^0 \to 2\mu$ puzzle" — once again, as we can easily notice, involves the familiar kaons.

A group of American scientists from the University of California studied the decay of long-lived neutral heavy mesons at the Bevatron of the Lawrence Radiation Laboratory. According to a theory based on the simplest and seemingly most reliable assumptions, at least one out of 150 million heavy mesons registered in the experiment should decay into a pair of light particles — mu-mesons with positive and negative electric charges. However, the experimenters found that the probability of this process was at least three times lower. What does this mean?

This very question, with rare unanimity, was raised by many physicists upon learning of the sensational results from the Bevatron, published in *Physical Review Letters*.

But there is still no answer. It is possible that the "$K_2^0 \to 2\mu$ paradox" is not a paradox at all but rather a new effect of *CP*-symmetry violation. Evidence for this would be the discovery of short-lived neutral kaon decays into two light charged particles.

> "But if no such decays are detected in the experiment," says Corresponding Member of the USSR Academy of Sciences A. Baldin, "then the catastrophe will deepen. Right now, this is the most pressing problem in elementary particle physics."

An experiment has already been conducted at the CERN accelerator, in which no cases of decay into two mu-mesons were detected among 4×10^7 decays of short-lived kaons.

Additional theoretical considerations might still justify the absence of such a process with a probability on the order of 10^{-7}. However, if this decay occurs even less frequently, it will likely lead to new "casualties" among the fundamental principles of nature.

Some of the best experimentalists have taken part in solving the "$K_2^0 \to 2\mu$ puzzle." Scientists have begun studying the decays of long-lived and short-lived heavy mesons at accelerators in Brookhaven, Berkeley, and the Argonne National Laboratory in the United States.

A team of researchers led by Candidate of Physical and Mathematical Sciences I. Savin from the Laboratory of High Energies at JINR is also now preparing to take on this new "height" that has opened before physicists.[15]

[15] The "$K_2^0 \to 2\mu$" continues to baffle scientists. This rare decay, happens almost exactly as the Standard Model – the rulebook of particle physics – predicts. The catch? Many researchers expected something beyond the Standard Model, like hidden forces or exotic particles, to nudge this process off course. Yet, it stays stubbornly on track, leaving little room for new physics to sneak in. Experiments like NA62 at CERN and KOTO in Japan have been hunting for clues, but so far, they've only confirmed the mystery: *the decay matches the old theory too well.* Scientists are left wondering if nature's hiding a secret trick – or if the Standard Model is tougher than they thought. – DM

5 Great Expectations

> Science is a building, not a pile of bricks, no matter how valuable that pile may be.
>
> *E. Wigner*

Conflict or Mutual Understanding?

Renowned theoretical physicist F. Dyson wrote in 1958,

> "I believe that a discovery comparable to Newtonian dynamics or quantum mechanics is unlikely to be made for at least a hundred years."

And he continues,

> "My view is that we are as far from understanding the nature of elementary particles as Newton's followers were from understanding quantum mechanics. It may well happen that all possible experiments involving collisions of various particles in accelera-

> tors will be conducted, all results will be carefully recorded and compiled, yet we will still have no real understanding of what is happening."

However, a more optimistic perspective was offered by Nobel laureate Academician I. Tamm in 1966:

> "I do not agree with the American theorist F. Dyson. The difficulties in constructing a new theory that must encompass everything we know so far as a special case are evident. Nevertheless, F. Dyson does not take into account the exponential growth of science in our time, nor the fact that an increasing number of people are engaged in physics. Einstein was a rare fluctuation, but given the vastly increased number of specialists today, the emergence of a new genius has become much more likely."

This is the view held by Academician V. Ginzburg. In early 1971, at a seminar at the Physics Institute of the USSR Academy of Sciences, he stated:

> "In the field of theory, it seems to me that we cannot speak of any real success. This has been the case for decades, and no one can predict when, at last, the 'ice will break.' But at some point, it will happen, and despite all the disappointments, this historic event continues to be awaited with unwavering and intense anticipation."

These candid remarks from leading physicists have introduced us to the main and most difficult challenge — the problem of constructing a theory of elementary particles.

Unfortunately, even today, as was the case several years

ago, R. Oppenheimer's words remain true:

> "For now, we do not understand the nature of matter, the laws that govern it, or the language in which it should be described."

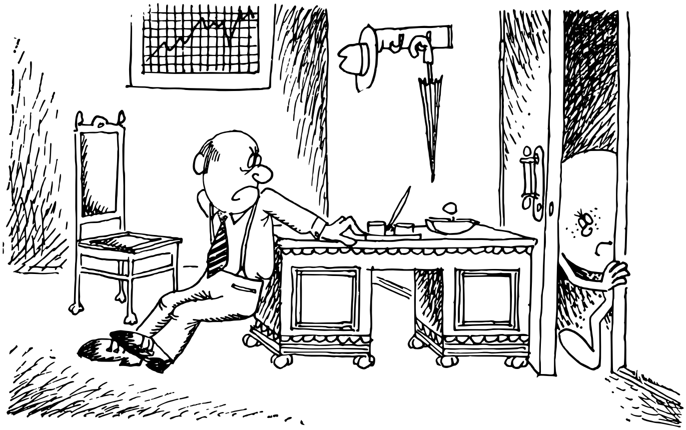
It is no secret that since the discovery of the first particles, science has made an enormous leap forward. Armed with powerful accelerators, researchers now venture into the deepest and most uncharted realms of phenomena. Popular books are already being written about the properties of elementary particles and how a unified classification has been established for many of the "citizens" of the microworld. New laws of nature have been discovered, such as the law of baryon number conservation — the very law that ensures our existence, as it prevents protons and neutrons from decaying into lighter particles. Muons and pions have already found practical applications in chemistry and solid-state physics.

Finally, elementary particles are used to analyse the great principles of nature — symmetry of space and time. So what exactly is meant by the claim that we do not understand the laws and language of nature?

Quantum theory does not even hint at the existence of the vast and diverse world of elementary particles. Physicists were so unprepared for the discovery of this world that, at first, they fiercely resisted acknowledging each newly found particle.

> "I recall," said P. Dirac recently, "how, in those distant times, I spoke with people working in the Cavendish

> Laboratory and observed the paths of particles in a magnetic field. They said that sometimes they saw an electron returning to its source. The experimenters had direct evidence of the existence of these new particles (positrons), yet they were unable to grasp the significance of what they were seeing."



And what about the discovery of the neutron? Bothe and Becker in Germany, as well as Irène and Frédéric Joliot-Curie in France, had already encountered neutrons, but only James Chadwick, a student of Ernest Rutherford who was familiar with his teacher's idea of a heavy neutral particle, was able to correctly interpret the new phenomenon.

Eventually, the psychological barrier was overcome, and the initial shock was dispelled. But what did this lead to? As we now know, scientists went from one challenge straight into another.

> “Since those distant times, the situation has completely changed,” said P. Dirac. “Now, new particles are proposed and introduced in great numbers on a continuous basis. People are eager to publish evidence for the existence of a new particle — whether it is discovered through experiment or merely based on some poorly justified theoretical idea.”

But why is such a situation possible? Because modern theory does not provide clear guidance on when to stop adding to the list of elementary particles. Hundreds of varieties exist! This is unsatisfactory, and physicists have long been questioning which of these particles are truly elementary and which only appear to be.

And there is no help from theory. *How could there be, when the theory itself does not even define what “elementary” means in the microscopic world?*

Physicists sense that, sooner or later, all these unresolved issues of the micro-world will lead to a fundamental revolution in theory, forcing a major reconsideration of concepts and principles. A new theory will emerge — one that, starting from a few general principles, will explain the entire diversity of particles, detailing the rules governing their interactions. With this theory, we will be able to predict what happens when any elementary particles collide.

This is the ultimate challenge facing theoretical physics today.

Simpleton or Genius?

There is much speculation about what the new theory of elementary particles might look like. Some believe its equations, in a highly condensed form, will encompass the entire physical picture of nature and incorporate all known properties of matter.

The distinguished Soviet scientist and historian of science, S. Vavilov, wrote as early as 1944 that

> "physics is the science of the simplest forms of matter. By its very nature, it has a certain tendency toward simplified approaches to phenomena."

He cautioned physicists against overly ambitious dreams that

> "the study of elementary particles should explain not only the fundamental forms of phenomena but, ultimately, the entire universe."

What this new theory will actually be like remains to be seen. For now, we must return to the immediate concerns of theoretical physics.

Why did quantum mechanics suddenly "stumble" and fail to bear the additional weight of elementary particle physics? To be fair, this criticism is not entirely directed at quantum mechanics itself. From the beginning, quantum mechanics was developed to describe atomic phenomena, a task it continues to perform excellently to this day. The real issue lies with the theory of elementary particles that emerged from quantum mechanics.

The foundations of quantum field theory were laid by some of the greatest scientists in the world, including W. Heisenberg, W. Pauli, P. Dirac, and V. Fock. P. Dirac, combining quantum mechanics with relativity theory, was the first to derive an equation describing an electron moving at nearly the speed of light. It was from this equation that physicists first learned of the existence of the positron.

To describe the remarkable properties of elementary particles — their transformations, their creation in nuclear reactions, and their annihilation — theorists developed a special mathematical framework known as the *method of second quantization*. But a method is not yet a theory. A true theory must explain the interactions between particles.

Gradually, quantum electrodynamics (QED) emerged — a branch of quantum field theory dealing solely with the electromagnetic interactions of elementary particles. It is often considered a prototype of an elementary particle theory. Even today, QED excels in its role, particularly in studying electromagnetic interactions between particles at extremely high energies.

However, no equally successful theory for strong interactions has been developed. Initially, it seemed that such a theory could be constructed in a manner similar to QED. The idea was simple: just as particles in QED exchange photons, here they would exchange pi-mesons — that was thought to be the only difference.

On the surface, this analogy appears valid. However,

strong interactions between particles at small distances are thousands of times more intense than electromagnetic interactions, often leading to the creation of an entire cascade of new particles. In theory, this results in infinite chains of equations. Mathematically, the theory becomes nightmarishly complex, and even if it were correct, no one knows how to obtain exact solutions to its equations.

When asked what hinders the development of a new theory of elementary particles, D. Blokhintsev responded:

> "We find it difficult to determine the issue — whether we lack a deep understanding of the phenomena, the key idea that could illuminate the vast array of facts, or whether we simply lack enough facts themselves. If fundamental contradictions with relativity theory or quantum mechanics were discovered, it would provide an immense impetus for new ideas."

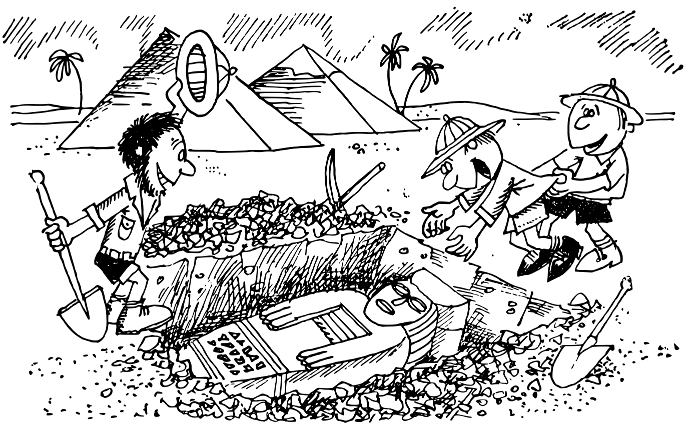
Another possibility cannot be ruled out. So far, the vast "mountains" of experimental data provide no clear guidance on the directions for searching for a future theory. In fact, these data themselves still await theoretical interpretation.

> "But, speaking among us theoretical physicists — how do we actually use these experimental results? Not at all. And who knows? Perhaps these experiments will bring us some absurd surprises, and some simpleton will manage to derive them theoretically from some elementary principle?"

Of course, the "simpleton" mentioned by the theoretical physicist R. Feynman would, in reality, be akin to a

genius — someone who could grasp the unique nature of the world of elementary particles based on existing knowledge. Both in the history of physics and in the history of other sciences, there are numerous examples of great discoveries made purely by approaching known facts from a new perspective.

A hundred years ago, the German businessman Heinrich Schliemann reread Homer's Iliad in a completely new way. Contrary to the prevailing scholarly opinions of the time, he treated all the events described in the epic as real historical occurrences. By meticulously following Homer's descriptions, Schliemann unearthed the city of Troy and discovered the treasure of King Priam.



An equally remarkable archaeological discovery was made by Howard Carter and Lord Carnarvon in 1922. They uncovered the tomb of Tutankhamun — completely filled

with priceless artefacts crafted by ancient Egyptian artisans — right in the Valley of the Kings, a site believed to have been excavated so thoroughly that not a single grain of sand had been left undisturbed. The leading archaeologists of the time were convinced that no new finds were possible there. However, based on previously discovered objects bearing Tutankhamun's name, as well as jars containing bundles of linen, Carter and Carnarvon, after a series of failed attempts, correctly determined the likely location of Tutankhamun's tomb — and ultimately found it.

Something similar could very well happen in high-energy physics. When?

No one knows.

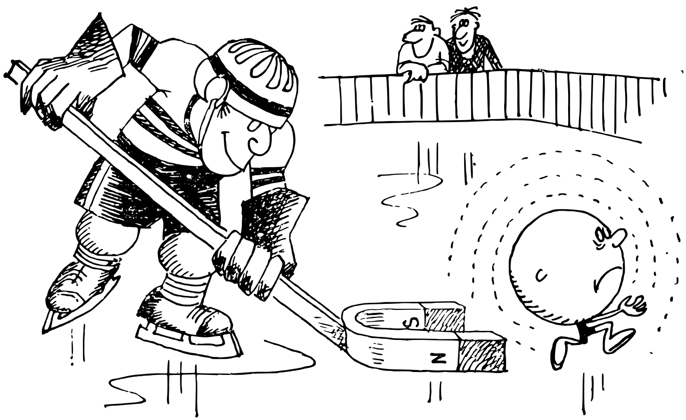
Serpukhov Speaks

Outside the car window, the ancient Russian town of Serpukhov suddenly appeared and just as quickly vanished. Another ten minutes of driving, and before us lay the city of physicists — Protvino, where, on the night of 14 October 1967, the most powerful particle accelerator of its time was first put into operation. Seventy billion electron volts of energy propel protons racing through its ring-shaped vacuum chamber, which stretches about one and a half kilometres!

Hidden from human sight, buried under the earth for radiation protection, lies the accelerator's magnet in the circular hall. This magnet allows physicists to keep hun-

dreds of billions of high-energy nuclear projectiles confined within the accelerator, moving at speeds close to that of light.

One hundred and twenty blocks, each 11 metres long, with a total weight of about 30,000 tonnes — this is the main "dispatcher" ensuring the correct motion of the protons. For comparison, the magnet of the Dubna accelerator, operating at 10 billion electron volts (10 GeV), is twice as heavy. The reason lies in the Serpukhov accelerator's "dispatcher" being of a higher "qualification," as it employs the principle of strong focusing.



Just as a hockey player controls the puck by striking it alternately from the right and left, preventing it from deviating from the intended path, so too does the Serpukhov accelerator's magnet guide the protons along a narrow circular track only 16 centimetres wide. This results in a

significant reduction in the magnet's mass.

But such precise control of the proton is only possible under one essential condition: the relative deviations in the magnetic field values from block to block must not exceed 10^{-4} (one ten-thousandth).

We still marvel at the craftsmanship of the builders of the ancient Egyptian pyramids. The skill of the ancient stonemasons astounds us — the massive blocks are so precisely fitted together that not even a sheet of paper can be inserted between them. And yet, this level of precision coexisted with a certain carelessness in the finishing of interior walls and the assembly of sarcophagi — places that were never meant to be seen.

Here, in the accelerator, there is no room for imprecision in unseen parts — if anything were carelessly made, the machine simply would not work. Yet the accelerator functioned perfectly from the very first start. This means the builders achieved a deviation in the magnetic field values of less than one ten-thousandth across different blocks, despite the fact that even steel from different batches exhibits slightly greater variations in magnetic properties.

Each of the 120 magnetic blocks was assembled from carefully mixed 2-millimetre-thick steel sheets obtained from different batches. Magnetic measurements were used to determine the optimal arrangement of these blocks within the accelerator ring. For stable operation, all the 240-tonne magnetic blocks had to be installed with an accuracy of 100 microns — an almost unimaginable chal-

lenge. Yet this, too, was successfully accomplished using specialised geodetic methods.

In the end, all difficulties were overcome, and physicists gained a new, powerful "microscope" for studying the microcosm. What, then, should they have directed it towards?

It is important to remember that the theory of elementary particles, like a house on a foundation, rests on several fundamental axioms and postulates that represent a natural extension of quantum mechanics and relativity theory. Therefore, the first decision was to use the new "microscope" to test the very foundations of the theory.

As early as 1956, Academician N. Bogolyubov, now the director of the Joint Institute for Nuclear Research, proved that the so-called dispersion relations — linking quantities that can be directly measured in experiments — follow from the general principles of modern theory.

What a unique opportunity! By measuring both the total probability of a particle interacting with matter and its probability of scattering at small angles, physicists were simultaneously testing the fundamental postulates of the theory. This created a crucial link between the foundations of modern physics and experiments in the world of elementary particles.

Two years later, Corresponding Member of the USSR Academy of Sciences I. Pomeranchuk derived another fundamental relation. Pomeranchuk's theorem also con-

nected fundamental axioms with experimental results.

At the Dubna synchrophasotron, dispersion relations were tested up to an energy of 10 GeV. No contradictions were found there, but some questions remained unresolved. Pomeranchuk's theorem was not confirmed by experiment, though this did not surprise anyone. The theorem stated that at sufficiently high energies, particles and antiparticles should interact with the same probability when colliding with the same target. However, it was unclear what energy range should be considered "sufficiently high." There remained hope that the theorem would be confirmed in future experiments.

It is clear how eagerly both theorists and experimentalists awaited the commissioning of the new, more powerful accelerator. The Serpukhov giant provided them not only with protons of record-breaking energy but also served as a true factory for producing unique secondary particles: pi- and *K*-mesons, antiprotons, and neutrinos.

The fundamental principles of the theory could now be tested on different types of particles simultaneously. One of the most convenient candidates for this purpose turned out to be the fascinating neutral *K*-mesons. These particles were produced when protons, moving at nearly the speed of light, collided with a target placed directly inside the accelerator's vacuum chamber. A moment later, at the exit of a 50-meter channel, the long-lived neutral *K*-mesons appeared — our familiar subjects of study.

Physicists considered these particles an ideal "gift" from

nature for testing Pomeranchuk's theorem. Each of them was a specific mixture of a particle and its antiparticle — the *K*-zero meson and the anti-*K*-zero meson. Now, by simply placing a material obstacle in their path, physicists could compare in a single experiment how particles from the matter and antimatter worlds behaved.

At the end of August 1970, scientists from forty countries gathered in Kyiv for a conference on high-energy physics. In the picturesque central district of the city, inside the hall of the October Palace of Culture, those deeply invested in the future of elementary particle physics convened.

The participants of this major scientific forum had to listen to five hundred reports. However, the most captivating and interesting presentations were those that reported on the results of experiments conducted in Serpukhov to test the dispersion relations and Pomeranchuk's theorem.

Experimental physicist and corresponding member of the USSR Academy of Sciences, Yu. Prokoshkin, presented the results of experiments on the interactions of protons and antiprotons, pi-plus and pi-minus mesons, and *K*-plus and *K*-minus mesons with nucleons at energies reaching 70 billion electron volts.

Great interest was generated by the experimental results obtained in studies of neutral *K*-mesons by a group led by Doctor of Physical and Mathematical Sciences I. Savin from the Laboratory of High Energies at JINR. These results received high praise from the distinguished American the-

oretical physicist Yang, who spoke during the discussion following the report.

The conference participants greeted Doctor of Physical and Mathematical Sciences V. Nikitin with applause as he took the podium. Under his leadership, scientists from Dubna conducted one of the first experiments at the Serpukhov facility to test the fundamental principles of the theory.

It is easy to understand why the Serpukhov experiments attracted such global scientific interest. The chairman of the conference's organising committee, Academician N. Bogolyubov, remarked:

> "Until now, many important theoretical conclusions have been based on experimental data obtained with accelerators operating at proton energies of up to 30 billion electron volts. What patterns will emerge at much higher energies? How will the experimental curves behave? Could they overturn the foundations of the theory?"

However, this time, there were no surprises. The discussion of the results obtained in Serpukhov convinced physicists that the axioms underlying quantum theory and the theory of relativity were also applicable to the description of elementary particles.

The Calm Before the Storm

There is a remarkable moment in nature that we call the calm before the storm. Everything falls silent, motionless,

and filled with anticipation. But if you look up, you will see low, moisture-laden clouds rushing across the sky. They gather into a massive, dark storm cloud, which grows heavier and sinks lower and lower.

The current period in elementary particle theory resembles such a calm. Yet, flipping through scientific journals or speaking with theorists quickly reveals the intense work underway. Experimental results are being meticulously studied, and numerous attempts are being made to explain them. After all, it is from these raw, unrefined experimental data that the next level of scientific understanding must be built.

Scientists do not yet know how to construct this new framework, but they are already beginning to see glimpses of its structure.

One thing is certain: the outdated concept of the point-like particle will not survive beyond the threshold of this emerging theory. A point is something that cannot be divided. Elementary particles seem to fit this definition — no one has ever observed half an electron or a third of a neutron. Yet, when high-energy particles collide, an entire cascade of new particles is produced. So what, then, is an elementary particle? *A fundamental, indivisible building block or a complex system?*

Think back to what was discovered when electron projectiles first probed deep into nucleons. The revelation of the proton's and neutron's internal structure and their spatial dimensions caused a sensation. And then came the

discovery of partons!

Yet, in theory, all particles are still treated as point-like. This is partly why calculations of particle masses often lead to infinite values. How can we incorporate into theory a new concept of the *elementary particle*, one that fully accounts for everything we have learned from experiments?

The situation with a particle's coordinate is no better. Werner Heisenberg's uncertainty principle states that in the microworld, it is impossible to simultaneously measure both the coordinate and momentum of a particle. However, the accuracy of each of these values individually is not fundamentally limited.

Suppose we need to measure the coordinate of a proton. How should we proceed? Any experimentalist will suggest that the proton's position can be determined by observing the scattering of incident gamma quanta. Let us follow this advice. Clearly, the closer the gamma quanta approach the particle, the more precisely we can determine its coordinate. But only high-energy quanta are capable of probing at such short distances. Very well — let us assume we have obtained such high-energy quanta and are excited at the prospect of conducting an ultra-precise experiment.

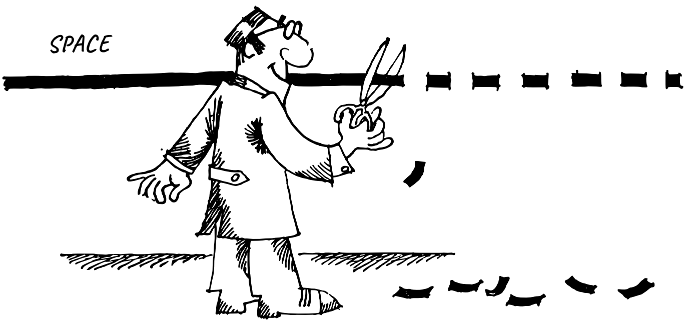
But what is happening? From the hydrogen target we placed in the beam of the highest-energy gamma quanta, new protons and antiprotons are flying out in all directions. Identical particles are being created, the coordinates of which we are attempting to measure. Now, we can *no* longer distinguish between the original proton and the

newly formed ones.

> "In my opinion," wrote Igor Tamm, "the foundation of a new theory will be a fundamental limitation on the accuracy of a particle's coordinate, considered in isolation, independent of its momentum."

Thus, even the classical concept of a particle's coordinate does not hold up in elementary particle physics.

Some scientists propose that on ultramicroscopic scales, space is not continuous but discrete. Based on the hypothesis of a fundamental unit of spatial length, attempts are being made to construct a new theory. However, real progress in developing these ideas remains limited.



This is precisely the drama of building a new theory! Somewhere ahead, like a magnificent vision with vague, blurred outlines, shines the grand palace of elementary particle physics. But in reality, physicists are faced with an unprocessed heap of experimental results. And for now, they do not yet know how to use this raw material for construction.

Let's Not Be Detectives

In the film *The Diamond Arm*, one of its characters, the well-known Semyon Semyonovich, describes his misfortune like this:

> "I slipped, fell, lost consciousness, came to — my arm was in a cast."

An experimental physicist would describe a nuclear reaction in much the same way:

> "I hurled high-energy protons at a substance, two particles collided, what happened during the process — I don't know, but I see that the detectors are registering new particles."

The fundamental difference between these two accounts is that Semyon Semyonovich actually saw what was done to his arm, whereas no one can accuse a physicist of deception.

Of course, scientists do not simply recount stories like these. They write research papers and give presentations framed in the rigorous mathematical language of S-matrix theory.

But neither the strict form nor the impressive name can hide the key fact: *the complete lack of information about what happens during the collision itself*.

The physicist, placing a hydrogen target in a beam of protons, knows precisely what is about to happen: a high-energy proton will collide with a proton in the target. These are the initial conditions of the reaction.

Remember: "I slipped, fell..." Stop! Everyone leaves the room. The accelerator is switched on. The electric field drives the particles faster and faster. Finally, the giant sling releases them. Collision!

But does this word convey any information beyond the mere fact that two fundamental "citizens" of the microworld met at enormous speed? How did they meet? What intermediate particles emerged? Which ones were reabsorbed?

Modern quantum theory cannot answer any of these questions. At such extreme collision energies, the mathematical framework of the theory completely breaks down. Remember: "Lost consciousness..."

Meanwhile, the instruments are already recording the results of the nuclear reaction. In the measurement centre, electronic devices — analysers — process the initial data. Finally, the researcher obtains the probability of the process of interest.

And this value, according to the fundamental principles of quantum mechanics, can indeed be expressed using a set of mathematical functions from the *S*-matrix.

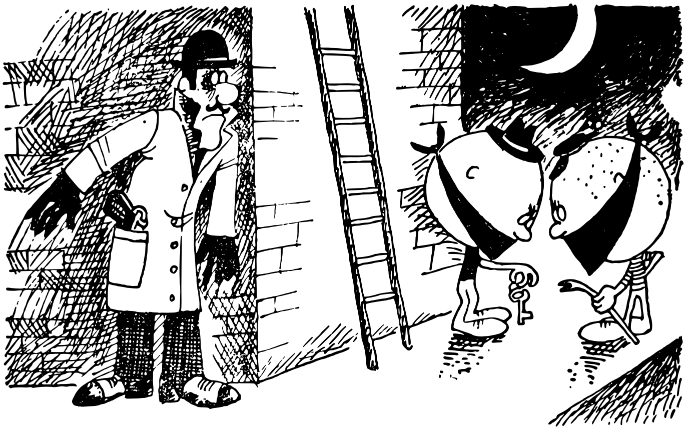
How is this any different from the famous: "Came to — my arm was in a cast"?

The *S*-matrix is a quantity that connects the initial state of a process with its final state — a quantity that is both measured experimentally and calculated theoretically. It is now the central link between theory and experiment, the

"hub" where theorists and experimentalists meet. The *S*-matrix is the language through which they communicate.

Well, they have met, analysed the data, and understood the experimental results. That means a theory can be created to explain the experiment! It can — but how?

One approach is the conventional one, guided by quantum mechanics. The behaviour of the particles involved in the reaction is studied in meticulous detail, step by step, much like a detective tracking a suspect, never losing sight of them, day or night.



But while a detective may still hope for success, a theorist's attempt is doomed from the start. No one has yet learned to solve the infinite chain of equations that, through the wave function, could describe the events occurring at the moment of collision.

This is why, as early as 1941, one of the founders of quantum mechanics, W. Heisenberg, proposed the idea that the S-matrix should form the foundation of the working apparatus of modern quantum theory.

"Let us not be detectives" — this is the essence of his idea. Let us not investigate what is currently beyond analysis. Instead, we must construct a theory whose equations can be solved. A theory that does not attempt to determine exactly what happens at the moment of "losing consciousness" — the collision — would be satisfactory to all.

An archaeologist does not need to know precisely who made an ancient artifact, with what specific tool, or on what exact day. What matters is knowing where and in which cultural layer the artifact was found. This closely parallels the initial conditions of a nuclear reaction, which are well known to the experimenter.

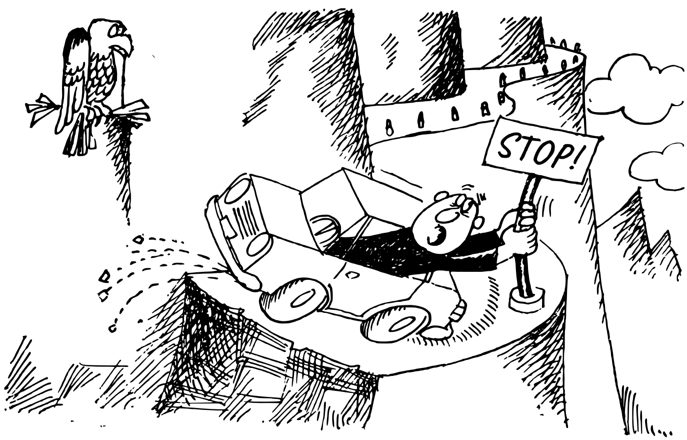
The archaeologist must then be able to directly study the discovered object. Similarly, the description of an archaeological find, like the experimental results in elementary particle physics, gains true value only after theoretical analysis.

An archaeologist will always try to at least approximately date a discovered artifact to determine its significance. But when physicists attempt to do the same — derive the elements of the *S*-matrix from equations — they encounter insurmountable difficulties. The "main road" in the matrix approach to building a new theory remains closed.

As a result, numerous detours emerge. Theorists have adapted to processing experimental data by simply postulating certain properties of matrix elements and proposing specific hypotheses without linking them to fundamental axioms.

Each of these alternative paths relies not so much on the rigorous logic of a pioneer but rather on intuition — an instinctive sensitivity to experimental data.

It remains uncertain whether these paths will ultimately lead to the final goal — constructing a coherent framework from a heap of scattered bricks. So far, these roads do not extend far before abruptly ending. Occasionally, these particular hypotheses allow for unexpected connections between different processes. But each time, only a very small number of bricks can be assembled into something whole.



> "The existing theory has a mosaic character," says D. Blokhintsev, Director of the Laboratory of Theoretical Physics at JINR. "It is possible to understand and even calculate individual phenomena. But often, a perspective that is valid for one group of phenomena does not align well with a perspective that explains another group. There is no overall picture — only separate fragments of it have been outlined."

From the mass of experimental facts, theorists are so far extracting only individual elements of the future edifice of modern physics.

But perhaps one day, someone, looking at this mosaic from a distance, will be able to place all the discovered pieces in their proper places and merge the individual hypotheses into a unified architectural plan — *the theory of elementary particles*.

A "Macro View" of the Microworld

Sometimes, it is absolutely necessary to see the entire picture of a process as a whole.

A single glance from an airplane is enough to recognise buried remains of houses in the ridges that hinder archaeological excavations. The mysterious lines carved into the stones of the Mexican plateau, when viewed from great heights, form a giant image of a bird.

The work of theoretical physicists, sifting through and examining each experimental fact, strongly resembles the

early stages of excavating a fascinating yet incomprehensible structure. Physicists are confident that, someday, the debris will be cleared away.

> "The truth is," says F. Dyson, "we can only push through one log at a time, and very few of them move when we push."

The unexplored world of elementary particles, still untouched by theoretical understanding, creates a "strange" impression. The English philosopher F. Bacon once wrote, "There is no true beauty without some degree of strangeness." One of our best popular science books — D. Danin's *The Inevitability of a Strange World* — bears a title that reflects this notion.

But is this strangeness truly inevitable?

Let us step back from scrutinising individual particles and their behaviour. Instead, let us try to take a "bird's-eye view" of the entire collection of experimental results, capturing in a single glance this new and astonishing world.

> "Do excessively large distortions of proportion, strange deviations from order, not ruin beauty?"

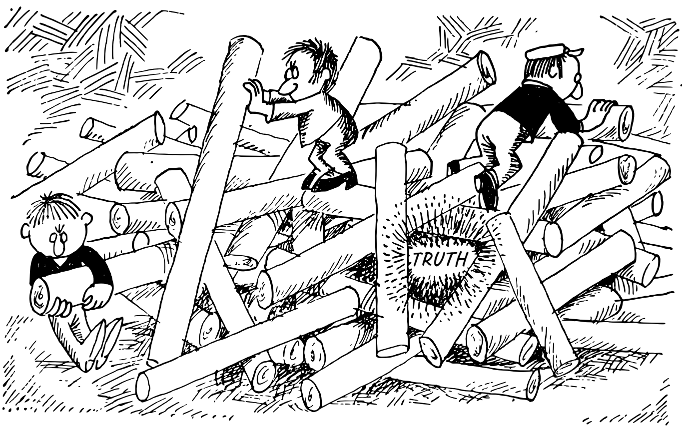
asks M. Gell-Mann. And he answers:

> For many years, one of the most important fields of physical science — the study of the structure of matter — suffered from a disease of strangeness. When physicists examined matter at the smallest distances, it appeared to them as an arbitrary mixture of individual elementary particles, among which no strict order could be discerned. Now, at last, the

> picture is beginning to clear up a little. The very word 'strangeness' has entered the physicists' vocabulary, and its share has diminished enough for the beauty of order to start emerging."

Particles that seem very different upon close examination — such as the proton and the neutron — become completely identical from the perspective of strong interactions. By introducing the new quantum number strangeness, M. Gell-Mann and A. Nishijima managed to integrate even the strange *K*-mesons into a unified particle classification scheme.

And the more details one manages to take in, the more ordered the once-chaotic pile of experimental results appears.



At the beginning of 1960, an article by the young theoretical physicist J. Sakurai appeared in an American scientific

journal. Its publication was preceded by a period of agonising deliberation: *to publish or not to publish?* Perhaps the main factor in the decision to go ahead was youth itself. It was easier for youth to overcome the fears experienced by every researcher hoping to achieve significant results.

> "You might think," says P. Dirac, "that a good researcher evaluates their findings completely calmly, without the slightest excitement, reasoning purely logically and developing their thoughts in a fully rational manner. This is far from the truth. A researcher is only human, and if they nurture great hopes, they also experience great fears."

Even before publishing his article, J. Sakurai was aware of the scepticism of his colleagues. "The particles you predict do not exist!" he heard from everyone. What inner confidence — perhaps even unconscious courage and determination — was required for Sakurai to take that final step! The controversial article was submitted for publication.

Theorists reacted coolly to its appearance, and many ignored it altogether. But the response from experimentalists was entirely different. It was not often that theorists provided such specific guidance. Mostly, they were engaged in "excavating" and analysing already obtained results.

Experiments were conducted at the world's largest accelerators. Before long, all three types of particles described by Sakurai were discovered. These were far from

ordinary particles. Without the discovery of vector mesons, as they were called, the idea of quarks might never have emerged.

M. Gell-Mann once remarked that nature is simple if one knows how to approach it. Historically, quantum theory of electromagnetic interactions was developed first, and only later, by analogy, did the theory of strong nuclear interactions emerge. The interaction between nucleons was conceived in the image and likeness of the relationships existing between charged particles. Electrons exchanged quanta of the electromagnetic field — photons — while neutrons or protons exchanged pi-mesons. But who can guarantee that this is the only possible and correct approach?

> "Our theory," said J. Sakurai, "in a way, echoes R. Feynman's remark that new ideas should be developed by asking: what if history had taken a different course?"

The path proposed by J. Sakurai started from the same "stove" as the previous one — an analogy with electromagnetic interaction.

Any high school student knows that an electric charge is the source of an electromagnetic field and that this charge determines the strength of interactions between charged bodies. But beyond that, we also know that electric charge is conserved with remarkable precision in all transformations of matter. Whether in nuclear reactions or collisions of elementary particles, the total electric charge of the par-

ticles before the reaction always equals the charge of all particles after the reaction. There is nothing new here. The law of conservation of electric charge was discovered long ago, and experimentalists are convinced of its inviolability.

The well-known theoretical physicist E. Wigner had already noted in the 1930s this dual role of electric charge: the fact that an intrinsic property of charge — its conservation — manifests dynamically by determining the strength of interaction. Much like a person's character, rooted in their temperament and embedded deep within their genetic code, manifests in their daily behaviour and actions.

The essence of the idea proposed by Wigner, Schwinger, Yang, Mills, and Utiyama was that the strength of any interaction should be linked to a conserved charge associated with that interaction.

In strong interactions, there are also three conserved quantities: *isotopic spin*, *hypercharge*, and *baryon charge*. But what if these quantities also manifest *dynamically* in strong interactions? If so, this could open the way to a new theoretical framework!

J. Sakurai set out to investigate whether these three conserved quantities corresponded to three types of interactions. His research revealed that, just as photons act as carriers of the electromagnetic field, nature should possess three types of vector mesons — carriers of the strong interaction — which were soon discovered by experimentalists.

> "If the proposed theory proves correct," wrote J. Sakurai, "then a natural question arises: could all fundamental interactions in nature — electromagnetic, nuclear, weak, and gravitational — be based on the conservation laws of intrinsic properties?"

Look at the vast scope this perspective offers — an exciting possibility of providing a unified "alphabet," a single theoretical foundation for the "multilingual" interactions of elementary particles! And most importantly, this possibility did not emerge from the application of rigorously structured analytical methods, as in the development of quantum field theory, but rather from the search for symmetry manifestations in particle interactions.

> "Amidst hundreds of attempts to construct a satisfactory theory of microscopic phenomena," writes Professor Ya. Smorodinsky, "a new method has emerged — a new way of reasoning that, at first glance, seems to lack clear foundations. This method of symmetries has proven to be highly effective, particularly in dealing with processes where the old theory is powerless."

By that time, M. Gell-Mann had already spent several years working on the classification of elementary particles, searching for a perspective from which all fundamental particles could be seen as part of a coherent system. When J. Sakurai's article appeared, Gell-Mann was perhaps more prepared than anyone else to grasp its ideas. Despite the skepticism of most theorists, he immediately applied its concepts to particle classification, leading to the develop-

ment of the *Eightfold Way*.

In his memoirs, cosmonaut V. Sevastyanov recalls that while flying over Warsaw, he decided to test the "macroscopic view" of Earth's geography from space. From his vantage point, he could simultaneously see the Scandinavian Peninsula, the Baltic Sea, Leningrad, the Adriatic, the Black Sea, and, ahead on the flight path, Moscow.

The ideas of Yang, Mills, and Sakurai allowed for a "macroscopic view" of the world of elementary particles, revealing its inherent order. All particles were grouped into several large families, each containing either eight or ten members. Within these families, the particles appeared mathematically equivalent and symmetrical to one another.

This provided not only aesthetic satisfaction but also practical benefits for the physics of the microcosm. The discovered "harmony of nature" played a crucial role in solving practical problems, making it possible for the first time to calculate the probabilities of processes involving particles within the same family. It also revealed dependencies between phenomena that had previously seemed unrelated.

Closing the 12th International Conference on High-Energy Physics in Dubna — the very conference where scientists first heard about experiments with kaons — D. Blokhintsev remarked that we were no longer far from our shared goal: *discovering new principles governing the world of elementary particles*. However, he added,

> "Skeptics might say: yes, you are probably right, and we are indeed close to the goal — provided we are heading in the right direction…"

Which of the current theoretical directions is correct remains uncertain. It seems likely that those scientists are right who believe that each competing theory contains a part of the truth and, to some extent, complements the others.

The Ghost Particle

The Serpukhov Accelerator… Let us return once more to this unique instrument of elementary particle physics. It allows us to probe the most hidden depths of matter, where every step forward is a discovery — though each new step becomes increasingly difficult.

It is hard to take one's eyes off the precise circular line of the accelerator's magnet. But what is this? The near-perfect symmetry of the Serpukhov magnet is disrupted. Between two of its straight sections, surrounding the vacuum chamber of the accelerator, a large spherical structure about five metres in diameter has appeared. Officially, physicists call it the "Dirac Monopole Detection Apparatus." Simply put, it is the latest design of a trap for one of the most elusive particles — one that scientists have long dreamed of encountering.

Electromagnetic interactions are perhaps the only area of modern physics where, as Professor Ya. Smorodinsky

puts it,

> "theory and experiment already agree to within a thousandth of a percent, leaving physicists in awe before the all-encompassing power of electrodynamics, which faithfully describes processes in galaxies and atomic nuclei alike."

Yet even in this field — quantum electrodynamics, which many regard as a prototype for the future theory of elementary particles — some "blank spots" remain. One of them is the astonishing fact that elementary particles, despite their vastly different masses, lifetimes, and other properties, all possess exactly the same electric charge — precisely equal to that of the electron.

The only explanation for this remarkable experimental fact was provided in 1931 by P. Dirac. His famous equation for the electron, which forms the foundation of electrodynamics, was the first to open the door to the antimatter world. It also led him to another significant conclusion — the possible existence of a particle with a magnetic charge, the so-called *monopole*.

If the monopole is real, then according to theory, it follows that all electric charges must always be integer multiples of a fundamental unit — exactly equal to the charge of an electron. After the discovery of the positron, scientists began to take Dirac's second prediction far more seriously.

More than forty years have passed since this idea was proposed. Yet even today, there are no competing hypothe-

ses. Naturally, experimentalists have long been striving to find the monopole. Like a mirage in the desert, it teases the imagination and compels scientists to devise increasingly sophisticated methods to detect it.

Do physicists know anything about this ghost particle? Do its searches not resemble a scenario well described in Russian folklore: "Go there, I know not where; find that, I know not what"?

A character in a detective play once remarked that he was "not trained to search for a ghost criminal — that he needed at least some concrete facts about him." The same can be said of the search for quarks and monopoles. Theoretical physics has not been particularly generous to either group of hunters. Both have only one firmly established clue: the fractional electric charge of quarks and the large magnetic charge of the Dirac-predicted monopole — seventy times greater than the charge of an electron.

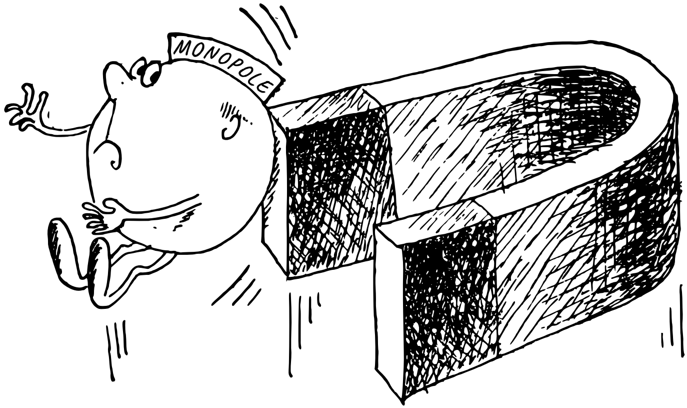
As you can see, the available information is sparse — very sparse. Yet, just as a skilled investigator can reconstruct a crime scene from the dust on a suspect's clothing, a physicist can infer the behaviour of a particle based on its magnetic charge.

Charge is the most crucial piece of evidence — it cannot be hidden. The monopole's defining characteristic is its exceptionally strong electromagnetic interaction, which sets it apart from all other elementary particles. If it were to pass through a photographic emulsion, it would leave a thick, dense track, much like a heavy atomic nucleus.

A monopole with such a large charge should be highly responsive to magnetic fields. Even the Earth's weak magnetic field would act upon it as powerfully as an electric field of 100,000 volts per centimetre affects an electron!

Could this unusual property be used to detect the monopole?

Long before the advent of powerful accelerators, the idea emerged to search for free monopoles in nature — particles that might have arrived on Earth as part of cosmic rays or formed in the Earth's atmosphere. But where should they be looked for? No one knows exactly where they might have landed after reaching our planet.



Here, the monopole's key characteristic comes into play: its magnetic charge makes it particularly sensitive to magnetic materials. This particle should drift along the magnetic field lines of our planet until it encounters iron or iron ores. Upon interacting with these materials, it would

accumulate in such deposits.

A tiny metal particle that enters the eye can be removed using a magnet. Similarly, scientists attempted to extract potential monopoles trapped in magnetic ores by applying a strong magnetic field.

In the United States, in the Adirondack Mountains, where magnetite formations reach the surface, scientists installed a powerful pulsed solenoid directly on the rock. The magnetic field at the solenoid's center and on the rock surface reached 60 kilogauss. Layers of photographic emulsion were placed at the top of the solenoid, ensuring that any monopole extracted from the rock and accelerated within the solenoid would leave a visible trace. However, when the emulsion was developed, it contained no desired "signatures."

Scientists also attempted to "extract" monopoles from iron meteorites, which had wandered through space for hundreds of millions of years. They searched for them in samples of magnetic minerals collected from the ocean floor, where fast monopoles — produced in cosmic particle collisions at energies reaching 10^{20} electron volts — could have accumulated over millions of years. Yet, these searches yielded no results.

Researchers tried to find traces of high-energy cosmic monopoles in mica and volcanic glass, but no such particle tracks were detected.

A few years ago, when the Apollo 11 mission brought

lunar soil samples to Earth for the first time, Professor Alvarez from the University of California conducted an original experiment. He decided to search for monopoles in lunar rock samples. Given the Moon's considerable age (3–4 billion years) and its relatively unchanged surface, it was a promising site where cosmic monopoles might have accumulated in significant numbers.

The precious lunar soil was repeatedly passed through an electric circuit made of superconducting material on a slow-moving conveyor belt. Since monopoles are charges — sources of powerful magnetic fields — a circulating electric current should have been induced in a closed conductor.

Almost all nine kilograms of lunar soil brought back by American astronauts were subjected to this test. However, no induced current was detected.

At first glance, one might conclude that monopoles do not exist in nature. Yet physicists did not make such a claim. After all, no one knows exactly how monopoles behave in matter. The experiments assumed that nothing had happened to the accumulated monopoles over time — but what justified this assumption?

Another uncertainty also arose. Some calculations suggested that the binding energy of a monopole in a substance would be on the scale of chemical bonds — just a few electron volts. However, other calculations indicated that this energy could reach hundreds of mega-electron volts. If the latter were true, extracting monopoles from

rock using a magnetic field would be impossible.

The first experiments in Berkeley with protons at just 7 GeV did not change the situation, nor did experiments with protons at 30 GeV. Physicists hypothesize that monopole pairs, like other elementary particles, might be produced in high-energy collisions between particles and matter. *But what energy is required?* Dirac's theory does not provide an answer. The energy needed to create a monopole depends on its mass, which remains unknown.

Thus, twenty years of relentless searches for this elusive particle have yielded no encouraging results. Over such a long period, scientists might have lost enthusiasm for the monopole problem.[16]

However, several years ago, the very author of the monopole theory, Paul Dirac, said:

> "After establishing the existence of the positron, I conceived the idea of a new particle — the magnetic monopole. This is justified by mathematical calculations of remarkable beauty, and we will be delighted if it turns out that monopoles indeed exist in nature, giving these magnificent mathematical results a real application."

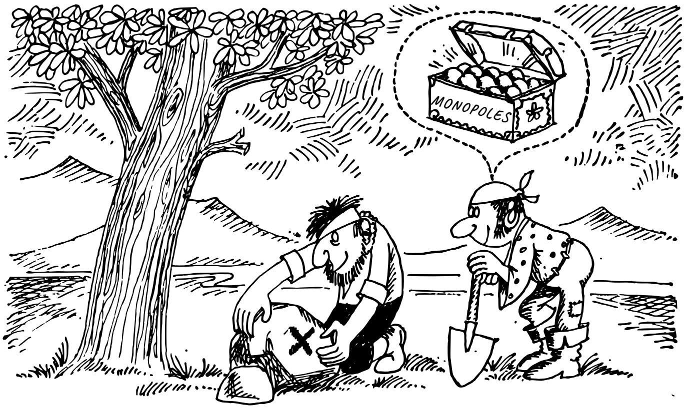
No, Paul Dirac did not abandon his prediction. The appearance of a spherical, satellite-like device in the chamber of the Serpukhov accelerator is the best proof that the search for this particle continues with undiminished interest. Serpukhov has opened a new chapter in the chronicle of Dirac monopole searches. The energy gained by particles in the

[16] As of 2023, magnetic monopoles — hypothetical particles proposed by Paul Dirac (1931) to explain charge quantization and predicted by grand unified theories (GUTs) and string theory — remain undiscovered. Extensive experimental searches in cosmic rays, particle accelerators (e.g., the LHC's MoEDAL experiment), and materials like lunar rocks have yielded no conclusive evidence. Theoretical uncertainties about their mass and interactions complicate detection efforts. While their existence would profoundly impact physics, confirming monopoles remains an open challenge. Research continues in both theoretical and experimental domains. – DM

accelerator is sufficient to create monopoles five times heavier than protons.

In the initial experiments at Serpukhov, a group of physicists from the Kurchatov Institute of Atomic Energy placed a target in the path of high-energy protons, where monopoles with different magnetic charge signs were expected to form. The accelerator's magnetic field should have deflected them in opposite directions toward storage films made of ferromagnetic material. After a year and a half — during which the films could have accumulated monopoles — they were exposed to a magnetic field exceeding 2×10^5 oersteds.

Yet again, failure! Not a single particle was detected.



These experiments were different from earlier attempts to find monopoles in nature, which resembled the search for a buried treasure with no known location. This time,

scientists knew exactly where the elusive particles should have appeared. Unfortunately, they attempted to detect them using an accumulation method, which had its own inherent limitations.

The only way to overcome these limitations was to detect monopoles immediately at the moment of their creation. This led to the development of a new setup at the Serpukhov accelerator. This time, an international team from the Joint Institute for Nuclear Research took part in the search for Dirac's particle.

Any charged particle moving through a medium faster than the speed of light in that medium can be detected by its electromagnetic Cherenkov radiation, named after its discoverer, Nobel laureate Academician P. Cherenkov. Today, the detection of ultra-fast particles via Cherenkov radiation is one of the key methods in high-energy physics.

This idea formed the basis of the new experiment. It exploited the fact that the Serpukhov accelerator could produce particles moving at speeds close to that of light in a vacuum. When such a particle enters a medium, it emits Cherenkov radiation. A small, carefully polished optical quartz cone was extended and fixed at the center of the vacuum chamber through a special automated system.

As particles created by proton beam collisions passed through this piece of quartz — the core of the Cherenkov detector — they were expected to immediately produce flashes of light. A complex optical system of lenses and photomultipliers, hidden beneath a protective casing, was

designed to collect and record this light.

The experimenters watched on a monitor as the target was struck by the proton beam, seeing it glow and shimmer spectacularly upon impact. It seemed almost unbelievable that, amid this dazzling light, the photomultipliers could detect the specific flashes belonging to a monopole.

Yet the physicists had no doubts. Their device was capable of detecting every monopole produced in the experiment with absolute certainty. According to the theory for which Academicians I. Tamm and I. Frank received the Nobel Prize, a magnetic charge emits 10^4 times more light than any other charged particle.

Moreover, a Dirac monopole would still be detected even if it were unstable and existed only for a fleeting moment.

> "I am absolutely convinced," said the experiment's lead scientist, physicist V. Zrelov, "that magnetic charges exist. There is no absolute theoretical prohibition, and coming up with such a prohibition is no easier than discovering a monopole. You already know how several fundamental principles of physics — perhaps even dogmatic ones — collapsed in the field of weak interactions. It seems to me that the more rigidly a theoretical principle forbids something, the more fiercely it is challenged by experimental physicists. I believe that someone will eventually be lucky enough to discover the monopole."

In 1972, the world's largest proton accelerator, with

an energy of 400 GeV, began operation in Batavia, near Chicago. A new machine — new objectives?

No, the objectives remained the same, as they were still unresolved. The unique setup by V. Nikitin, featuring a hydrogen jet target, was transported across the ocean along with its creators for measurements in a new energy range of protons. More than half of the proposed experimental projects in Batavia were dedicated to the search for quarks and the Dirac monopole. The persistent search for the intermediate boson, the carrier of weak interactions, continued.

Experiments with neutrinos of previously inaccessible energies were of great importance, as they held significant potential for testing Steven Weinberg's new theory of weak interactions. One of the leading theorists called this theory the greatest achievement of the past 15 years. As we can see, efforts were concentrated on a few critical problems.

In 1969, theoretical physicist J. Schwinger further narrowed the scope of experimental challenges by proposing a hypothesis that all elementary particles contain a fundamental component called the *dyon*. But what about the quark model of matter?

Both monopoles and quarks are several times heavier than protons and are linked to the idea of new forms of matter. J. Schwinger connected the "fates" of these two particles by unifying the problem of electromagnetic interactions — the Dirac monopole — with the problem of classifying elementary particles — quarks. If the monopole

were discovered, it would immediately explain why all electric charges are quantized. However, at the same time, the very concept of quarks — particles with charges of 1/3 and 2/3 of an electron's charge — would vanish.

The dyon, proposed by J. Schwinger, offers a solution. According to theory, only the dyon — a particle with a magnetic charge — can possess a *fractional* electric charge.

The fractional electric charge of this hybrid is compatible with the integer charge, which is a multiple of the electron charge, found in elementary particles that lack a magnetic charge. If dyons were discovered, they could even help explain the violation of *CP* symmetry in weak interactions.

Will experimentalists be able to provide clear answers to the questions posed by theorists? Will these answers be sufficient for constructing a new theory of elementary particles? That remains unknown. Perhaps the issue will be resolved in the coming years, or perhaps the answers will lead to an entirely new set of questions. The only certainty is "the boundlessness of the unknown and the endless joy of the journey of discovery."

★ ★ ★ ★ ★

It is no coincidence that in the finale of Copenhagen's *Faust*, written by Niels Bohr's students and performed at the *kapustnik* following the 1932 theoretical conference, Mephistopheles declared:

> *Experiment is like revelation:*
> *Though no trace of theory within it lies,*
> *A new page of nature's contemplation*
> *Summons us to thoughts yet to arise.*

6 Big Science

With Voltage Of Any Tension,
With The Distant Frontier Of
Imagination,
I Choose The Future Amidst A Heap
Of Yet Unpublished Instruments.

P. Antokolsky

Then And Now

What is the secret of the "craft" of modern experimental physicists?

In the past, a person unfamiliar with science could, while standing behind Rutherford, easily imagine themselves participating in the discovery of the atomic nucleus, simply by observing the rare star-like flashes on the scintillation screen. Just as we, watching a coin maker at work, can picture ourselves as his collaborato rs because we see

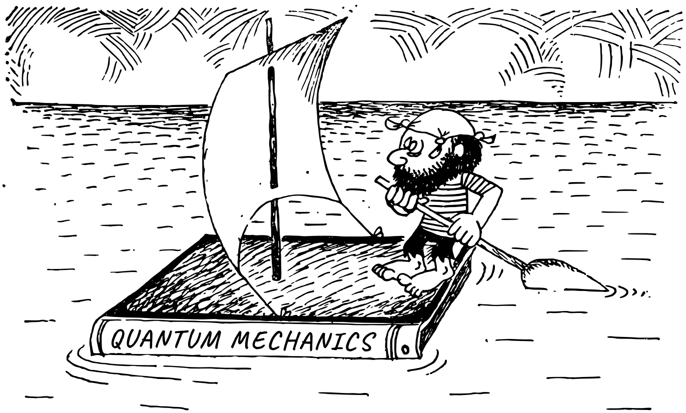
all his sequential operations.

In his decisive experiment leading to the discovery of the neutron, Chadwick used only a single device — an ionization chamber. The appearance of an electrical pulse at its output indicated the entry of a charged proton into the chamber. The clarity of this experiment was less than that of working with a scintillation screen, yet still considerable. If one moved the alpha particle source aside or removed the piece of paraffin placed in front of the chamber — where neutrons knocked out protons — the mechanical counter would fall silent.

E. Rutherford made great discoveries using primitive equipment, often assembling it himself, sometimes from tin cans. At that time, physicists did not work with accelerators — those had yet to be invented — but with radioactive sources, dealing with at most two types of particles. And what "convenient" particles they were! Stable, like electrons and protons, or long-lived, like neutrons. Their detection posed no difficulties: *they differed in the degree of ionization they produced*. Even a novice could easily distinguish an alpha particle from an electron by the magnitude of the pulse from the ionization chamber.

Yet, the simplicity of early 20th-century experiments was only apparent. Despite the primitiveness of the equipment, experiments leading to the discovery of the atomic nucleus and elementary particles were incredibly challenging because they marked the very first steps into the microcosm. Matter unexpectedly revealed itself to scien-

tists in an entirely new way. Navigating this vast, uncharted ocean of the unknown was daunting without the guiding compass of theory. Quantum mechanics was only beginning to take shape, and there was no talk yet of a theory of elementary particles. Charting the right course under these complex conditions was a task only the greatest physicists of the century could accomplish.



The centre of gravity in experimental high-energy physics has now shifted more towards implementing experiments that are already known in principle. The objects under study are so complex that no "simple" methods exist for their investigation. Today, any experiment in high-energy physics is as much more complex than the early ones as atomic clocks are compared to sundials. The work of experimental physicists has long since lost the appeal of its original simplicity.

Only in the memories of veteran scientists remain those not-so-distant times when “the fate of a physical experiment was decided by a single good glassblower, and the presence of a lathe in the laboratory was considered grounds for optimistic forecasts.”

The creation of a unique setup — something that is now considered a “standard” installation — requires enormous material resources. Its cost reaches several million roubles. Therefore, every experiment conducted, for instance, at the Serpukhov accelerator, is first discussed at the scientific council of the Institute for High Energy Physics. Only after receiving approval do experimentalists proceed with constructing the necessary setup.

And this, to put it plainly, is an extraordinarily difficult task. It can only be accomplished by those who possess the fundamental secret of their craft — those who combine extensive knowledge of the properties and behaviour of elementary particles with exceptional experimental skill.

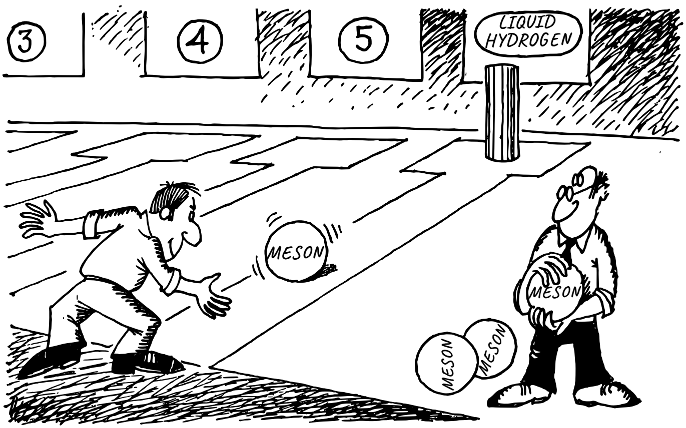
Bathing in Liquid Hydrogen

The verification of Pomeranchuk’s theorem using K^0-mesons (the aim of the experiment) is not a groundbreaking discovery but, as the group leader I. Savin put it, “an entirely transparent matter.” More than fifteen years ago, as soon as the nature of these particles was understood, it became clear how they could be used to test the foundations of the theory. However, the proposed experiment was so com-

plex that only the modern level of experimental technology has made this idea practically feasible.

A setup for testing this fundamental theorem has been built in Serpukhov. Even a professional athlete would need more than ten seconds to run from the point where the heavy neutral particles are born in the accelerator's vacuum chamber to the end of the entire experimental complex, which stretches nearly 100 metres in length. Let us take this distance at a leisurely pace, stopping at the key points of the setup.

In the first fifty metres, nothing unusual happens to the neutral kaons. They pass through several deflecting electromagnets and magnetic lenses, which filter out unwanted particles, and then dive into collimators that shape them into a beam.



The mesonic channel, along which we continue, care-

fully delivers the maximum possible number of particles to the liquid hydrogen target. What happens to the long-lived K^0-mesons after their immersion in liquid hydrogen?

For low-energy particles, it was already known that they must transform into short-lived K^0-mesons. The question now was how the same long-lived K^0-mesons would behave when colliding with the target at extremely high energies. If Pomeranchuk's theorem is correct, and the particles and antiparticles that make up K^0-mesons interact almost identically with the protons in the target at high energies, then significantly fewer short-lived mesons should be produced.

Physicists imposed strict requirements on the state of hydrogen in the target. It had to maintain a constant temperature and density, but most importantly, it had to remain absolutely free from boiling! Tiny bubbles forming throughout the target's volume were a serious threat, as they subtly altered its thickness — an effect that could not yet be accounted for. Meeting all these conditions was no easy task, even when working with a small liquid hydrogen target. However, in this experiment, to increase the likelihood of kaon-proton collisions, a three-metre-long target was required!

A three-metre-long stainless steel tube filled with liquid hydrogen was placed inside another tube about half a metre in diameter, with the air in the gap between them evacuated to prevent boiling.

However, this introduced a new challenge. The experi-

ment required that no additional obstacles be placed in the path of the K-mesons as they entered and exited the target. Yet, such obstacles were present in the form of dense end walls. The target windows had to be sealed with Mylar films only 120 microns thick. However, the thin film bent under the pressure of the liquid hydrogen towards the vacuum. This was unacceptable since the mesonic channel emitted a beam of particles with a diameter of several centimetres. If the film deformed, the effective length of the hydrogen target would vary for different particles, leading to inconsistent experimental results.

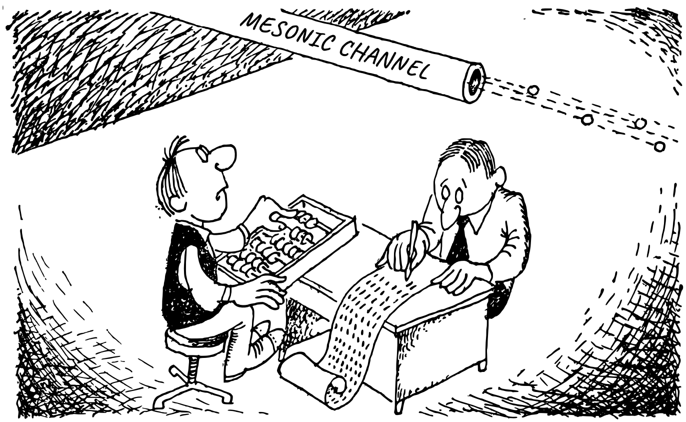
The solution, as always, came unexpectedly and turned out to be quite simple. The target windows were made from two layers of Mylar. A tiny hole was punctured in the inner film to equalise the pressure on both sides without allowing liquid hydrogen to seep into the gap between the films. This original window design, combined with a specially developed pressure stabiliser for the target, allowed the amount of hydrogen in the particle path to be maintained with a precision of 0.05% over an extended period.

Lightning in a Box

After passing the target with its complex cryogenic system and two control panels, we arrive at a point where physicists seem to have only one remaining task. Here, just three metres from the end of the mesonic channel, they simply need to count the number of short-lived neutral

mesons emerging from the target. The number of these mesons directly corresponds to the difference in interaction probabilities between K^0- and anti-K^0-mesons with hydrogen. It seems straightforward, does it not?

However, the heavy, short-lived K^0-mesons appear from the target only for a fleeting moment before immediately decaying into lighter pi-plus and pi-minus mesons. This is the main challenge of the experiment. It is not enough to simply register the two new particles; it must also be proven that they originated from a primary kaon — a short-lived K^0-meson. This must be done in the presence of an enormous number of background particles coming from both the accelerator and the target.



By analysing the angle between the pi-mesons and their energy, the mass of the parent particle can be determined. If this mass matches that of a K^0-meson, it is likely that

these charged particles are indeed the decay products of a kaon, that is, pi-mesons. To be absolutely certain, the motion direction of the suspected K^0-meson is compared with the direction of the mesonic beam incident on the target. These two directions *must* coincide.

For all these measurements, an experimental setup is required that can identify the particles of interest among millions within billionths of a second and record their spatial coordinates with sub-millimetre precision. It would also be useful to see the passing particles! Of course, elementary particles themselves are invisible, but their tracks — trajectories — have long been made "visible" using photographic emulsions. These emulsions were successfully used in the early days of microscopic physics and are still in use today. A block, or as physicists call it, a "bucket of emulsion," will be used in the experiment to detect Dirac's monopole at the CERN accelerator.

Unfortunately, for verifying Pomeranchuk's theorem, such a device is unsuitable since it cannot be actively controlled. In recent years, a new instrument has emerged in particle physics — the spark chamber. Many problems, including the challenge posed by K^0-mesons, could not have been solved without this device.

The design of the spark chamber is relatively simple. Inside an airtight box filled with an inert gas, metal plates or wires are arranged at certain distances from each other. When a charged particle passes between the plates, it strips electrons from atoms, leaving behind ionised atoms and

free electrons. A high voltage applied to the plates accelerates these atomic fragments, enabling them to knock more electrons from atoms. The newly freed electrons and ions continue this process, creating an avalanche — a channel of ionised gas. This opens the path for an electric discharge, and in the gas-filled gaps where the particle has passed, a breakdown occurs, producing bright sparks. These sparks make the particle's path visible or accessible for automatic measurements.

Soviet scientists made significant contributions to the development of this advanced technique. They managed to intervene in the discharge process by shortening the high-voltage pulse applied to the chamber's plates. This allowed them to halt the process at the streamer stage, where the electric field only initiates charge avalanches — streamers — without leading to a full breakdown. As a result, it became possible to measure track coordinates with high precision, even when a particle passed at an angle to the plates.

In recognition of their achievement in developing the streamer spark chamber, a team from the Institute of Physics of the Georgian SSR Academy of Sciences, led by G. Chikovani, and a joint team from the Institute of Physics of the USSR Academy of Sciences and the Moscow Engineering Physics Institute, led by Doctor of Physical and Mathematical Sciences B. Dolgoshein, were awarded the Lenin Prize in 1970.

Despite its advantages, the spark chamber recorded the

paths of not only the desired pi-mesons but also any other charged particles. How could the chamber be made to ignore unwanted particles?

The only solution was to activate it exclusively for particles originating from neutral K^0-mesons. Nearly forty metres of the experimental setup for verifying Pomeranchuk's theorem were filled with complex instruments designed to make this possible. The experimenters had a precise understanding of the trajectory geometry of the pi-mesons from the decay of short-lived K^0-mesons, extending to the end of the massive setup.

Nine spark chambers before the magnet and the same number after it are required to accurately record the spatial coordinates of particles. In numerical terms, this system can detect a coordinate change as small as 1 millimetre over a distance of five metres.

However, if the spark chambers operate continuously, they will be overwhelmed by tracks of background particles, making it nearly impossible to find the ones of interest. On the other hand, it is impossible to predict in advance which incoming particles should be recorded and which should be ignored. Some time is needed to distinguish between them.

This is where the key advantage of the spark chamber comes into play. When a charged particle passes through, it leaves a trail of ions and electrons between the metal plates. However, this trail remains invisible until high voltage is applied. In the microsecond it takes for the particle

to pass through, the atomic debris does not have time to disperse. As a result, the chamber, even when activated with such a delay, can still make the particle's path visible.

Thus, physicists have an entire microsecond at their disposal. In this brief moment, they must not only identify the correct particles but also issue the command to activate the spark chambers.

From Monologue To Dialogue

How different the working conditions of experimental physicists are now compared to thirty years ago!

Back then, the interaction between the researcher and the instrument was a slow conversation made up of long monologues. Recall how Ernest Rutherford, filling a chamber alternately with air, nitrogen, and hydrogen, calmly counted the flashes from ejected hydrogen nuclei. James Chadwick first measured the number of protons knocked out of paraffin by neutrons, then removed the paraffin and methodically confirmed that no protons were now being emitted.

Such a pace of "conversation" is unimaginable in modern high-energy physics experiments. Now, a rapid dialogue is needed, ideally without pauses.

One long-established tool in the experimenter's arsenal is the scintillation counter. When charged particles pass through, they produce a light flash, which a sensitive

photomultiplier tube instantly converts into an electrical pulse. By measuring the pulse amplitude, it is easy to distinguish protons from electrons and mesons — provided their energies are low. However, for relativistic particles moving close to the speed of light, all pulses appear the same, making it impossible to identify particle types this way. But high-energy physicists recognised one crucial advantage of this instrument: it provides a signal from each passing particle extremely quickly — within 10^{-9} seconds — exactly what is needed for modern experiments.

Thus, around 50 scintillation counters were placed throughout the experimental setup. They were positioned before the spark chambers, before and after the magnet, and in such a way that any particle of interest had to pass through them. Now, by analysing the order in which the impulses arrive — matching the particle's trajectory through the setup — scientists can identify pi-mesons resulting from the decay of neutral kaons and issue the command for the spark chambers to activate and record the event.

But it is easier said than done — finding a pi-meson! Even the quickest human cannot accomplish this within fractions of a second. That is why special electronic "logic" circuits take over. Within a billionth of a second, they analyse the impulses from all the scintillation counters, and if two particles simultaneously trigger all the counters in the specified sequence, the electronic circuit identifies them as the desired particles and "authorises" the activation of the spark chambers. At that moment, in each chamber section where a particle has passed, a spark discharge oc-

curs.

Electrical impulses from the numerous wires in each of the 18 chambers then begin transmitting data about the particle's trajectory coordinates (*x* and *y*) at that specific point in space.

Thus, we have traversed the entire length of the meson channel and the experimental setup designed to register short-lived neutral kaons produced in the liquid hydrogen target.

However, what we have observed does not yet cover all the key components of the installation. Away from the main setup, in the "experiment house," where researchers remain during accelerator operations, racks hold several hundred blocks of electronic equipment packed with tens of thousands of transistors. These receive all the impulses from the setup. In yet another room lies a device that collects and processes all the data. Here, the operation of every instrument, both collectively and individually, is monitored. Without this control, an installation integrating the most advanced experimental science and technology would become nothing more than a showcase of modern equipment.

Naturally, this device is an electronic computer.

> "Previously, before the development of the methodology for conducting experiments with a computer system," said I. Savin, "carrying out such experiments would have been pointless."

The volume of data generated by the experiment is so immense that even a computing machine, straining its "memory" to the limit and operating at maximum speed, barely manages to process and record the trajectories of the required particles onto magnetic tape.

Another session at the accelerator has concluded. The physicists return with a precious load of experimental results, encoded in magnetic tapes. A new phase of work begins — one that no longer requires the accelerator but instead demands another computer to process this "raw" data.

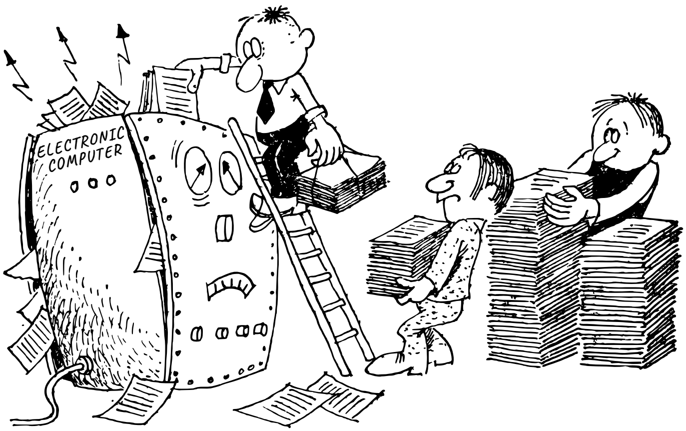
In Dubna's main computing centre, a powerful and high-speed computer is installed. Using a specially designed mathematical "reconstruction" programme, it reassembles the complete picture of the decay of short-lived neutral kaons from trajectory fragments. The machine independently determines the decay point, the angle between the pi-mesons, and the energy of these particles based on their deflection in the magnetic field.

Once all kaon-related events from the liquid hydrogen target are reconstructed and their characteristics recorded in a structured format onto new magnetic tapes, these tapes undergo further processing.

Despite the logical circuits diligently performing their tasks, some of the recorded events — though superficially resembling the nuclear reaction being investigated — may turn out to be random occurrences. Thus, the final judgement is left to the physicists.

The magnetic tapes containing results obtained by the international team of physicists, led by I. Savin, were duplicated and further processed in Dubna, Prague, and Budapest.

Several years of intense work by a large team of scientists were required to test the Pomeranchuk theorem on protons, neutrons, and deuterium isotope nuclei. The fundamental theorem of modern physics was confirmed: the greater the energy of the particles, the smaller the difference in behaviour between these particles and their antiparticles.



Target – A Jet of Hydrogen

"They say ideas are expensive. That is true. And yet, in our practice, the 'drama of ideas' most often unfolds not in

the lofty realm of thought but in the practicalities of their implementation," say the experimenters.

If an experiment with kaons required a uniquely large and high-quality target containing a considerable amount of hydrogen, then the proton-on-proton scattering experiments conducted in Serpukhov under the leadership of V. Nikitin demanded an ultra-thin target with a density of just a millionth of a gram per cubic centimetre.

Any shell enclosing such a gaseous hydrogen target would have hopelessly ruined the results. The essence of the experiment lay precisely in observing how fast protons behave when colliding with a pure hydrogen target. Thus, at the Laboratory of High Energies of the Joint Institute for Nuclear Research (JINR), a unique hydrogen jet target, operating inside the accelerator chamber, was created for the first time in the world.

Even the device's creators now find it difficult to say whether there were more supporters or opponents of the idea at the outset. Even leading scientists doubted its feasibility, and not without reason.

In the Serpukhov accelerator, protons gained energy up to 70 billion electron volts. They moved along a closed loop in a vacuum chamber, which had been carefully evacuated to a pressure of 10^{-7} millimetres of mercury. Even the slightest degradation of the vacuum would sharply reduce the number of accelerated protons: colliding with air particles, they would hit the chamber walls and drop out of the acceleration process. Their movement resembled the

erratic motion of a hockey puck struck by a novice player's stick.

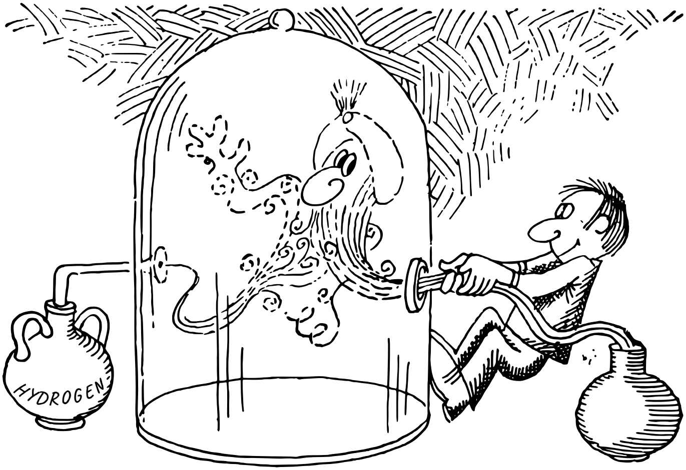
And under such stringent vacuum conditions, it was necessary to regularly inject enough hydrogen into the chamber to significantly increase the pressure throughout the entire volume of the accelerator. A sudden vacuum breach in the accelerator chamber during an experiment would have led to electrical breakdowns in the high-frequency systems, putting the unique accelerator out of operation for an extended period.

The challenge faced by the designers resembled that of the hero in an Eastern tale who unwittingly unsealed a bottle containing a trapped genie. To avoid finding themselves in a similar predicament, they decided to release the genie — a jet of gaseous hydrogen — into the vacuum chamber while preparing another "bottle" on the opposite side: a vacuum pump.

Again and again, the staff of the cryogenic department at the Laboratory of High Energies of the Joint Institute for Nuclear Research (JINR) conducted experiments on models until the high vacuum and the dense gas flow no longer contradicted each other, and the structure of the future device began to take shape.

A jet of gaseous hydrogen, released from a special device at supersonic speed, passed through the beam of fast protons inside the accelerator chamber — at that moment, it served as the target. It was then captured by the "neck" of a helium condensation pump, which indeed resembled a

wide-mouthed bottle. In a fraction of a second, the pump subdued the unleashed genie, transforming the hydrogen gas, ready to disperse in all directions, into a stationary and completely harmless frost of solid hydrogen.



And so, in March 1968, the day arrived when the transport department workers of JINR began moving the completed installation to Serpukhov. It was one of the first to appear in the vast, still-empty accelerator hall. A period of intense, months-long work began to prepare the equipment for operation on the new machine. Finally, the days of round-the-clock measurements and continuous experiments arrived.

While physicists were analysing the obtained results, design engineers continued refining the jet target methodology. It was necessary to achieve a narrower jet width to

eliminate errors in determining the emission angles of secondary particles during interactions between accelerated protons and the target. Moreover, for some experiments, the jet target was still insufficiently dense, which prolonged the operating time on the accelerator.

A solution was found. The jet was made denser by transitioning from a supersonic gas jet to a stream of more slowly moving liquid hydrogen droplets and solid hydrogen particles. The width of the new condensed hydrogen target was reduced by a factor of four, its density increased tenfold, and the amount of gas injected into the accelerator was reduced by two to three times.

In the spring of 1972, a group led by V. Nikitin, along with several members of the cryogenics department who participated in the creation of the jet target, travelled to America. They conducted experiments with the new, unique device at the newly launched world's most powerful accelerator in Batavia, operating at an energy of 400 GeV.

The results of the initial measurements obtained on this installation were already presented in the summer of 1972 at the High Energy Physics Conference in Batavia.

"Industrial" Science

The experimental hall of a modern accelerator. A hundred-metre-long installation operates entirely automatically under the steady hum of electromagnets. Does it not resemble a factory with an automated production line? The only

difference is that one can approach a factory line at any moment and make adjustments if something goes wrong. For physicists, however, this issue is tied to shutting down the accelerator. Moreover, they do not see with their own eyes the "parts" being processed by their installation.

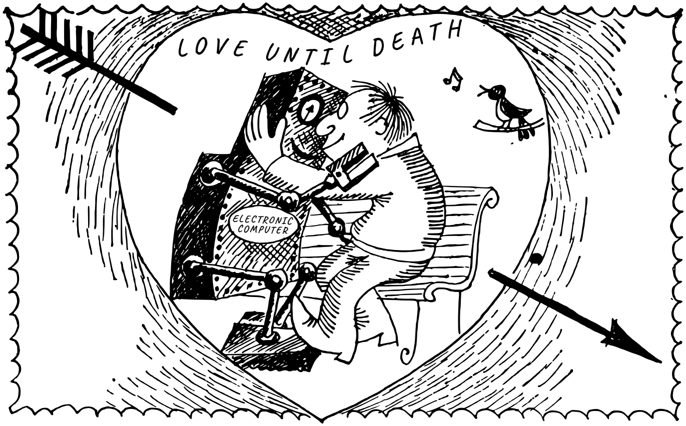
A production line is typically overseen by several operators. The same picture is observed here. For instance, in an experiment testing Pomeranchuk's theorem, four people oversee the operation of 50 scintillation counters, 18 spark chambers, and a large magnet around the clock. Two monitor the electronic circuits that receive and transmit experimental data to the computer. The other two work directly with the computer, tracking the data input and checking the performance of individual counters and the entire setup.

The computer is the *heart* of modern experimental devices. Physicists have long been using computing machines. However, in the past, they were employed only at the stage of data processing. Now, at the largest accelerators, they are entrusted with "conducting" the experiment itself.

It is interesting to note the admission of V. Nikitin, the leader of one of the most significant and fascinating experiments conducted in Serpukhov:

> "Experimental physics today is unimaginable without computers. It is astonishing how quickly human psychology changes. Just ten years ago, many of us would occasionally peek into the hall of the 'old lady'

> M-20, tagging along with some excursion. A mocking smile would cross our lips at the sight of the strings of octal machine code... And now, we cannot live without it — love until the death!"



In Serpukhov, V. Nikitin's group recently completed a 700-hour experiment. The BESM-3M machine continuously sorted and recorded information. Without the machine's assistance, simply recording the experiment's results would have required a stack of notebooks a kilometre high!

> "Working on a modern large computer," said V. Nikitin, "is a pleasure. This is especially true when the reading device does not eat the cards, the magnetic tape does not reverse, the tape recorder does not erase your personal library, a parallel task does not throw your program out due to a lack of space on the magnetic drum, and the female operators smile as they inform you that, although your time has run

> out, they are willing to give you an extra 30 seconds (of course, at the expense of tomorrow's session)."

Not long ago, experimental physicist Luis Alvarez remarked in his Nobel lecture that

> "the time has passed when, in articles signed by a single physicist, one could read at the end: 'I would like to thank so-and-so for developing the equipment and obtaining most of the results.' "

Today, researchers, engineers, programmers, and highly qualified laboratory technicians with university degrees are equal co-authors in collaborative work. The paper on testing the Pomeranchuk theorem using a hydrogen target was signed by 28 authors! Among them were several physicists, electronics engineers, spark chamber specialists, and staff from the JINR computing centre.

Of course, this does not mean that small groups of scientists are no longer active in particle physics. In such groups, thanks to the ideas generated by their leaders, it is sometimes possible to achieve brilliant results even with relatively modest resources. This is particularly true for physicists working with accelerators up to 1 GeV (1 billion electron volts). However, for machines operating at tens of GeV or more, experimentalists are compelled to form large teams. In such collectives, which utilise modern industrial equipment and computing machines, there is a distinct division of labour.

> As research becomes more large-scale," said Academician B. Kadomtsev, "it often happens that an individual scientist is left with relatively minor tasks.

> This is a certain drawback of modern science — an increasing number of people are forced to solve such tasks."

Undoubtedly, the nature of work for each member of a large scientific collective has changed. Yet, these large teams are now capable of tackling scientific challenges that researchers of the "craft and manual" era of science could never have even dreamed of.

Members of large research teams generally enjoy working with complex experimental setups. Their enthusiasm does not need to be fueled. However, the situation is often more difficult for a recent graduate who joins a research institution. Having been trained on classical examples from the history of physics, they may not even be aware of the existence of modern "big science," where large teams work on highly complex projects, the results of which may not be expected for several years. Yet, they aspire to make a groundbreaking discovery quickly. When they eventually realise that this is simply impossible, they often experience disappointment.

Why does this happen?

> "Science is now extremely complex," says Academician B. Kadomtsev, "and only a few manage to achieve outstanding success. It is clear that if a university graduate sets such a goal in advance, they are likely to face failure. Over time, they may return to their 'youthful maximalism,' but on a different foundation — after sufficiently developing their abilities and ensuring that their ambitions align with their

> capabilities."

Indeed, the nature of science has changed significantly over the past three or four decades. However, "scientific research has retained its old-fashioned spirit of relentless creative pursuit."

"Magic Wand"

Creative pursuit... It was this drive that continued to stir the already ageing father of atomic physics, Ernest Rutherford. By 1924, he had managed to split all the light nuclei that could be penetrated by the alpha particles emitted by radium. But what next?

The renowned scientist F. Aston wrote at the time:

> "Now comes the inevitable period of stagnation while we await the discovery of new tools for research."

Naturally, the one who felt this stagnation most acutely was the very discoverer of the atomic nucleus himself. He had no means to "cultivate" the vast "nuclear frontier" before him. If only he had particles with higher energies...

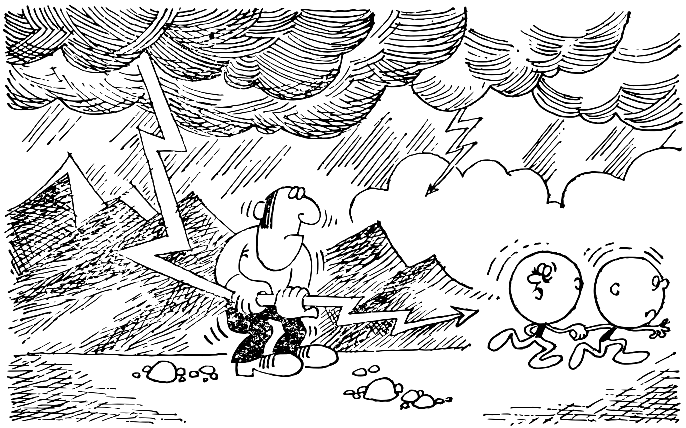
Rutherford asked his assistant, Kay, to investigate whether it was possible to assemble a system of batteries or dynamo machines to generate strong electric fields.

When Kay presented Rutherford with the estimated cost of such a system — insignificant by today's standards — Rutherford dismissed the project "as if it were a red-hot brick."

For those of us living in the era of magnificent accelerators, such as those in Serpukhov or Batavia, it is difficult to imagine that, in Rutherford's time, the creation of high-voltage sources seemed like an insurmountable challenge.

A group of Italian physicists attempted to use lightning discharges in the mountains to accelerate particles. However, conducting experiments with such an unpredictable voltage source was, at the very least, inconvenient.

Then came 1932, when Rutherford's team — his "boys," John Cockcroft and Ernest Walton — produced a beam of protons accelerated in a discharge tube to nearly one million electron volts. At the time, this was a groundbreaking achievement. For the first time in history, nuclear reactions induced by artificially accelerated particles could be observed.



Thus began the era of accelerators in elementary parti-

cle physics.

The next major step was the creation of the circular accelerator — the cyclotron — by Ernest Lawrence, whose design has influenced modern giant machines. However, the cyclotron's operating principle did not allow for particle energies beyond several tens of millions of electron volts. Therefore, the history of accelerators that have played a crucial role in exploring the microcosm can be said to have truly begun in 1944. That year, the Soviet scientist V. Veksler announced the discovery of the principle of *phase stability*. The path to high energies was opened.

Now, accelerators with energies of several billion electron volts and beyond have become a kind of "magic wand," capable of instantly creating a "spectacular display" of elementary particles.

Consider how this process unfolds. Protons accelerated to enormous energies collide with a target, positioned either inside a vacuum chamber or at the exit of the proton beam from the accelerator. In all directions, neutrons, protons, mesons, and resonances scatter...

Unfortunately, not all the energy of the colliding particles is used to generate new ones. The mass of fast, accelerated protons is significantly greater than that of protons in the stationary target. Upon collision, a substantial portion of the "projectile" proton's energy is spent on the motion of both particles, leaving only a small fraction available for the creation of new ones. Only when two particles approach each other at equal speeds in opposite directions can their

entire energy be converted into interaction energy. But it is impossible to move a target at near-light speed to meet accelerated protons.

"Why not?" scientists wondered. The idea was worth pursuing: if the speeds of the colliding particles were close to the speed of light, the effect of their interaction would not just increase fourfold, as predicted by Newtonian mechanics, but perhaps by a factor of 4,000. When two electrons with an energy of one billion electron volts collide, the interaction effect would be equivalent to that of an accelerator with an energy of 4,000 billion electron volts!

How could this be achieved? Perhaps an accelerator without a conventional target? Or an accelerator with a target "spun up" to the speed of light? But in that case, the target would become just another beam of accelerated protons. This led to the idea of a collider with counter-propagating beams.

However, do not imagine two separate accelerators positioned opposite each other, crossing their beams like rapiers. In reality, it is a single accelerator that "pumps" two metallic rings — like inflating bicycle tires — with protons moving in opposite directions.

Two interwoven rings, each 300 meters in diameter — this was the setup of the recently launched collider at CERN. Protons, injected into the rings from a conventional accelerator at an energy of 23 billion electron volts, interacted as if they were particles with an effective energy 50 times greater — 1,100 billion electron volts!

Scientists observed proton-proton scattering for the first time at an energy unattainable by any classical accelerator. A complex system of magnets, weighing 5,000 tonnes, kept the particles on a magnetic track inside a vacuum chamber approximately 1,000 meters long and ten centimeters in diameter. It is worth noting that this entire apparatus was developed over five years by a team of 300 physicists.

However, these new accelerators had one significant drawback, their weak point. The Achilles' heel of colliders with counter-propagating beams was the low density of the moving target — the second beam. Its density was hundreds of millions of billions of times lower than that of a conventional stationary target. This is why such accelerators began to be built only recently, despite the idea of their construction being known for a long time.

"Colliding two particles," said Academician G. Budker, "is about as difficult as arranging a meeting between two arrows — one shot by Robin Hood from Earth and the other by William Tell from a planet orbiting Sirius."

Physicists must ensure that the paths of the particles intersect as frequently as possible. The CERN rings are designed with a geometry that allows protons to meet at eight specific interaction points.

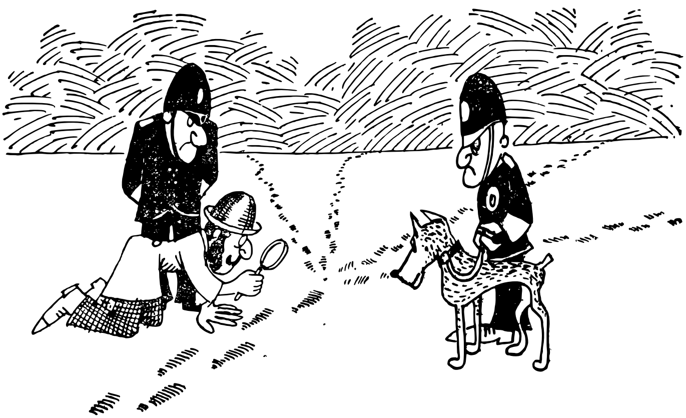
At the Institute of Nuclear Physics in Novosibirsk, under the leadership of Academician G. Budker, research is being conducted on colliding proton-antiproton beams. A facility is being constructed where protons and antiprotons will collide at an energy of 25 GeV each, equivalent to a conventional accelerator operating at 1,200 GeV. The paths of matter and antimatter particles will intersect. There is hope that if quarks exist and their mass does not exceed 25 proton masses, they will be detected.

"Ultra-high energies are the domain of colliding beams," says Academician G. Budker. Therefore, physicists in Novosibirsk are already discussing a new project involving proton-antiproton colliding beams, corresponding to an accelerator with an energy of 2 million billion electron volts. A conventional accelerator of such energy would have to be the size of the Earth's diameter, and its cost would approach the total national income of the entire planet.

However, even colliding-beam accelerators are complex and bulky devices. Moreover, they still rely on the conventional, classical method of acceleration.

In 1956, Academician V. Veksler proposed an entirely new method for accelerating elementary particles. Until then, all machines were designed to accelerate each particle individually. Although we speak of a proton beam and discuss its density, all these protons, racing side by side through a vacuum chamber along a magnetic track, are essentially independent of each other.

V. Veksler was the first to realise that particles do not need to be accelerated individually and that "all the power lies in the collective." He proposed an idea that initially seemed utterly fantastic. Even such accelerator specialists as E. Lawrence and McMillan did not immediately understand it.



Indeed, it is difficult to imagine that protons, for example, could be accelerated by an electric field not created by external sources but by a cloud of electrons. Electrons

with an energy of just 1 MeV already move at nearly the speed of light. If a large cloud of such electrons were to capture and drag protons along with it, their speeds would eventually equalise. However, protons are 2,000 times heavier than electrons, meaning their energy would be greater by the same factor. As a result, their energy could reach several billion electron volts.

It is possible that this idea will be realised in a new method for generating specialised particle beams for nuclear physics research.

Physics at a Distance

At the end of April 1953, during a lunch in the garden of a hotel at the American Physical Society meeting, two future Nobel laureates met: the already well-known experimental physicist L. Alvarez and the then-unknown D. Glaser. Glaser was very sorry that no one would hear his ten-minute presentation because it was scheduled as the very last talk of the conference.

> "At that time, the era of slow airplanes," recalled L. Alvarez, "even fewer people attended the last talk of a conference than they do now (if that's even possible). I thought I might not be present for it either, so I asked him to explain to me what he was going to talk about. That's how I first heard from D. Glaser about his invention of the bubble chamber. His work made a tremendous impression on me, and I immediately felt that this might be the very breakthrough idea that particle physics desperately needed."

At the time, spark chambers did not yet exist, and experimentalists had no idea how to begin studying the recently discovered and puzzling strange particles — kaons and hyperons. It was clear: to study reactions where negative pi-mesons interact with protons to produce two neutral strange particles, physicists needed to see the entire process from start to finish with their own eyes. In other words, they needed to find the point where the track of the pi-meson ends and, after some interval, two "forks" of tracks from charged particles appear, indicating the decay of the neutral strange particles.

And what about the problem of the neutral sigma-hyperon? The reaction of its decay became the subject of a joke by V. Weisskopf at one scientific conference. The renowned theorist caused laughter in the audience by showing a completely blank photograph taken in a Wilson cloud chamber and declaring that it was evidence of the decay of a new neutral sigma-hyperon into two other neutral particles. This joke perfectly captured the helplessness of experimentalists in the face of such reactions before the invention of the bubble chamber.

Photographic emulsions are unsuitable for studying reactions that involve a break — a gap corresponding to the passage of neutral particles. The first successful track detector, the Wilson chamber, was also inadequate for this purpose.

The Wilson chamber played a crucial role in the history of understanding the microcosm. At the beginning of the

20th century, some physicists still doubted the existence of not only elementary particles but even atoms. The Wilson chamber, which made it possible to see the tracks of individual charged particles and ionised atoms, dispelled all such doubts. Niels Bohr, in a letter to Ernest Rutherford, vividly captured the excitement of physicists who, for the first time, saw the transformation of an atomic nucleus with their own eyes:

> "When you learn that a proton and a lithium nucleus simply combine into an alpha particle, you feel that it could not have been otherwise, though no one had dared to think so."

Even today, experimental physicists continue to use the Wilson chamber, but its application is limited. The vapour inside has a low density, making the probability of interactions — such as those between negative mesons and protons within the chamber — very small.

This was the state of experimental physics at the time when Donald Glaser developed a new tracking device — the bubble chamber. Its working principle is simple: in a superheated liquid contained within the chamber, vapour bubbles rapidly form along the path of a passing charged particle. These bubbles emerge on the "trail" of electrons and ions left behind by the particle.

The chamber could be filled with different liquids, carefully selected to facilitate the study of specific reactions. To investigate interactions of various particles with protons, it was filled with liquid hydrogen, which has a high density. In the liquid hydrogen of the chamber, the entire chain of

reactions — from the birth to the decay of any elementary particle — could be observed.

Bubble chambers have become one of the most widely used instruments in laboratories around the world. The reason is clear. When accelerators were less powerful, nuclear reactions typically produced only two or three particles at a time, which could be tracked using several scintillation counters. However, with the advent of higher-energy accelerators, researchers gained the ability to study multiple particle production processes, involving five to fourteen different types of particles. In such cases, bubble chambers proved to be the most suitable tool.

During a conversation with Luis Alvarez at an American Physical Society meeting, Donald Glaser showed him his first photographs of bubble tracks. These images were obtained using a small glass vessel, about 1 centimetre in diameter and 2 centimetres long, filled with diethyl ether. Just four years later, a bubble chamber with a diameter of 180 centimetres was already in operation.

Resonances that travel a few nuclear radii before decaying and rare reactions involving the production of strange particles — all of these became observable to the "keen eye" of the bubble chamber, which continuously scrutinised the microscopic world. In 1960, Glaser's discovery was honoured with the Nobel Prize.

It was in a two-metre bubble chamber at Brookhaven National Laboratory that the famous omega-minus hyperon was discovered, significantly bolstering the standing

of the Eightfold Way theory. In 1970, Argonne National Laboratory commissioned a 3.6-metre-long liquid hydrogen bubble chamber specifically for neutrino experiments. A year ago, the French nuclear research centre in Saclay built a bubble chamber with a diameter of 4.7 metres.

A modern bubble chamber is a complex system, resembling an industrial plant with extensive vacuum, power, gas, and electronic systems. As an instrument for studying the fundamental building blocks of matter, it incorporates the latest advancements in low-temperature physics, cryogenic technology, scanning optics, and many other fields of science and engineering.

Each such device is developed over many years by large teams of scientists, cryogenics specialists, engineers, and technicians.

The tracks formed in the liquid hydrogen inside the chamber are photographed through observation windows made of optical glass, each weighing several hundred kilograms. When the first chambers were being built, the challenge of creating a large window sometimes seemed insurmountable. Luis Alvarez, one of the pioneers of large bubble chambers, recalled:

> "Once, while reviewing the list of papers presented at a recent cryogenic engineering conference, I came across one titled: 'A Large Glass Window for Observing Liquid Hydrogen.' Eager with anticipation, I rushed to find the paper, only to discover that it described a metal Dewar vessel with a window... just one inch in diameter!"

At the Joint Institute for Nuclear Research (JINR) in Dubna, a two-metre liquid hydrogen bubble chamber was constructed. Physicists named it *Ludmila*, and its development required the intense efforts of most of the laboratory's staff. In terms of financial and labour costs, Ludmila exceeded those of a complex experimental setup for studying neutral *K*-mesons by a factor of five to ten.

Encased within a massive magnet and surrounded on all sides by pipes, tubes, and auxiliary structures, the chamber does not present a particularly elegant appearance. It is no surprise that, during its inauguration, one attendee asked:

> "Why give such a poetic name to this monstrosity? Could it be for the same reason that the most beautiful female names are given to the terrifying typhoons of the southern seas?"

The director of the High Energy Laboratory, Professor A. Baldin, explained the choice of the name as follows:

> "The name 'Ludmila' arose more or less by chance, but many people liked it: 'Ludmila' — 'dear to people.' We want 'Ludmila' to bring people great joy in scientific creativity and significant scientific discoveries."

On 1 January 1970, *Ludmila* was filled with liquid hydrogen for the first time. Hardly any high-energy physics experiment could proceed without substantial involvement from cryogenics specialists, but in the creation of the liquid hydrogen bubble chamber, their contribution was decisive. Therefore, the initial startup of *Ludmila* was overseen by the staff of the cryogenics department. Its head,

Doctor of Technical Sciences A. Zeldovich, described with near-documentary precision the most tense moments of the chamber's launch:

> "The chamber is almost full. Stop! Another blockage. Changing the filter. Something always 'fails' during the first run. We continue filling. Days and nights begin to blur together. Finally, the liquid hydrogen level appears and reaches the top glass. We seal the chamber. Heating. Another blockage, and yet another. Then an urgent rewiring in the control panel. And finally, we switch the chamber to its operating cycle. Two staff members persistently search for tracks with the naked eye. But soon, the assembly of the photographic system is complete, and recording begins. The first test strip of film."
>
> An entry appears in the operations log:
>
> "8 January, 14:20, Shafranov detected tracks on the film!!!"
>
> Everyone is elated. The maximum programme is achieved. We also confirm another experimental fact — when uncorked, the champagne bottle's cork does not reach the ceiling, only the overhead crane."

In February 1971, the chamber was dismantled for transportation to Serpukhov, to the Institute for High Energy Physics. The process of dismantling, transport, and reassembly of *Ludimala* was an extremely intense task that lasted six months. At times, up to seven trucks per day were sent from Dubna and received in Serpukhov by the staff of the hydrogen chamber department.

The head of the installation sighed with relief when the

700-kilogram optical glass was successfully inserted into the chamber window. By September, *Ludimala* had been reassembled from its individual components at the new site. Hydrogen testing began. The scientists now had to breathe life into the chamber once again.

> “The first impression,” recalled A. Baldin, ”that remained with most people who became familiar with the chamber’s systems was: ‘It is impossible for such an endless number of components and connections to function reliably — there are simply too many of them.’ ”
>
> “In any case, it is impossible for everything to work immediately after assembly — that never happens,”

was the categorical opinion of some well-known specialists.

However, the electromagnet — one of the largest and most critical parts of the entire setup — functioned perfectly from the very first attempt, “without any smoke,” as sometimes happens. It created a magnetic field of up to 30,000 gauss in a six-cubic-metre shaft, where the hydrogen bubble chamber was lowered inside a *Dewar* (thermos).

The first startup of the chamber proceeded strictly according to schedule and without failures. By late September–early October, *Ludimala* was already operating in a proton beam with an energy of 35 billion electron volts, producing its first photographs of nuclear reactions.

Now, physicists faced new challenges: before begin-

ning regular irradiation experiments, they had to address both major and minor imperfections. As attractive as a large magnetic field may be for experimental physicists, it becomes even more valuable when precisely measured — especially within the volume of the hydrogen chamber under operating conditions at a temperature of –248 °C.

Specialists from Leningrad designed a mechanism capable of autonomously operating inside the assembled chamber, controlled remotely via a teleoperation system. The working conditions for this device were hardly any easier than those of the famous *Lunokhod* lunar rover.

On 14 January 1972, the official inauguration of the *Ludmila* liquid hydrogen chamber took place in Protvino. Academician N. Bogolyubov stated:

> "There are only a few such chambers in the world. However, this one has a significant advantage. It will be the first major installation of its kind to operate on the world's largest Soviet accelerator of charged particles in Serpukhov. The Dubna liquid hydrogen chamber will enable institutes and universities of socialist countries, including the Soviet Union, to participate in research on elementary interactions and elementary particles at the highest energies ever achieved by a giant accelerator. Scientists from different countries will be able to obtain and study hundreds of thousands of images of unique nuclear 'events.'"

A new term even emerged — *remote physics* — which signifies that high-energy physics is no longer limited to

those directly working with the largest accelerators and installations like *Ludmila*. The bubble chamber, resembling a factory not only in its technical complexity but also in its volume of *production*, generates millions of images per year. These images impartially and indiscriminately capture *all* elementary particles that enter the chamber and record *everything* that happens to them within its volume.

After an initial analysis of these photographs using a specialised viewing machine, all the extracted information is recorded onto magnetic tape. In this convenient format, these *semi-processed* data, whether from the large chamber or from experiments such as the test of Pomeranchuk's theorem, can be distributed to various institutes. This represents the emergence of a new approach to research — one conducted remotely. *Remote physics*, as this method is now sometimes called, is expected to bring a much larger number of researchers into the forefront of microcosmic studies in the near future.

A scientist working thousands of kilometres away from Serpukhov could discover new particles, nuclear reactions, or previously unknown types of interactions between elementary particles.

7 Fruits And Roots

> Recognise the sign of phenomena
> And you will have power... .
>
> *Great Yazu*

From Cobblestones To Antimatter

Today, everything is explained with numbers in hand. Mathematicians and biologists, cyberneticists and demographers, economists and essayists all appeal to them. Let us start with them as well.

The construction of the recently launched largest accelerator in Batavia, USA, with an energy of up to 400 GeV, cost the state 250 million dollars. A similar machine, currently under construction at CERN — the institute uniting scientists from Western European countries — will cost approximately the same amount.

The expenses for designing and manufacturing experimental equipment for accelerator research account for a good half of the accelerator's total cost.

No other field of fundamental research, apart from elementary particle physics, can "boast" such colossal expenditures. But this is not a whim of scientists, nor a failure of financial or planning bodies. It is an urgent necessity.

Every new grain of knowledge about the world of elementary particles demands ever greater efforts. Advancing in this field is challenging not only for an individual laboratory or institute but even for an entire country. The solution lies in the development of international scientific cooperation, within which the creation and effective use of many costly installations have become possible.

Recently, at a meeting dedicated to the approval of the 400 GeV proton accelerator project, Professor J. Adams, director of the CERN-2 laboratory, expressed the opinion that the next-generation accelerator — with an energy of 10,000 GeV — would be a "triad-tron," a machine created through the joint efforts of the USSR, the USA, and Western Europe.

But has particle physics become too expensive? American scientists have calculated that the total expenditure on fundamental research from the time of Archimedes to the present does not exceed the cost of the current ten-day gross national product of the United States! This leads to an unexpected conclusion: spending on fundamental science is growing more slowly than society's wealth. Yet

its contribution to the development of modern material production is enormous.

It is interesting, however, to hear what physicists themselves have to say about this.

> "As history shows," said Corresponding Member of the USSR Academy of Sciences A. Baldin, "the discovery of fundamental laws of nature sooner or later has a profound impact on society. The strength of fundamental science lies in its ability to generate qualitatively new ideas. And with their help, it becomes possible to suddenly, in a single leap, solve many of the most complex practical problems.
>
> A compelling example is the penetration of new methods of quantum field theory (developed specifically for elementary particle theory) into solid-state physics. And solid-state physics — superconductivity, semiconductor physics, metal physics, and more — is directly related to technology."

> "It is impossible to predict in advance the practical applications of things that have not yet been studied,"

said Corresponding Member F. Shapiro.

> "Here's an example from the past. J.J. Thomson discovered the electron, and as a result, we have electronics, televisions, and semiconductors. But he was simply curious to study how currents flow in gases. Today, we cannot say with certainty what practical applications nuclear forces will have in the future. We can only assert that if they are not studied, no applications will appear. If new knowledge emerges, inventions in this field will follow. But if there is no

> knowledge, then all we can do is write science fiction novels."

> "I could give many examples," says Academician N. Bogolyubov, Director of JINR, "where seemingly purely theoretical fundamental research laid the groundwork that led to the emergence of new fields of technology. In my deep conviction, penetrating the secrets of the deep structure of matter must lead to significant, perhaps completely unexpected, practical applications. Of course, everyone is interested in the fruits of science, and that is natural. But at the same time, attention must also be paid to the deeply buried roots of the tree on which such fruits can grow."

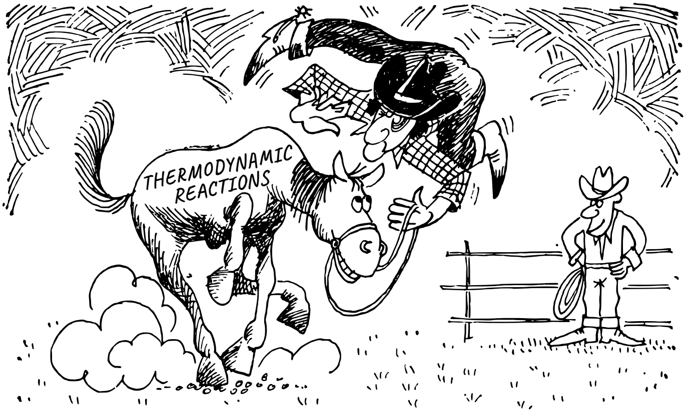
Nobel laureate A. Szent-Györgyi put it well:

> "It takes only an average level of intelligence to recognize the immense contribution that modern science has made to the development of humanity — to see in science the leitmotif of progress and the force that sets the tone for our twentieth century. It is impossible not to see that practically all of us are indebted to science, and if we were to remove its fruits from our lives, nothing would remain of our civilization."

Now, let us try to look into the future. It is well known that the level of technical development of a civilization depends on its energy capacity. Specialists in extraterrestrial civilizations (yes, such experts already exist!) define several stages in the development of civilization — starting with the creation of a unified planetary energy system and ending with controlled energy extraction from star

clusters.

Before penetrating the microworld, humans relied on energy sources they discovered by chance on Earth's surface: fires made from branches, coal, and oil. Later, they learned to harness the energy of falling water.



Of all the natural sciences, only elementary particle physics has provided humanity with a new source of energy — the atomic one. This is a classic example of how fundamental research into heavy atomic nucleus reactions suddenly solved the pressing problem of energy production for humanity.

Scientists have discovered that the fusion of two light nuclei also releases enormous energy — thermonuclear energy. However, controlling it has not yet been achieved. This is currently a top-priority practical challenge, with large scientific teams working on its solution.

For the development of civilisation, it is important not only to obtain energy in ever-increasing amounts but also to concentrate and control its release.

A primitive human used only a negligible fraction of the energy contained in, say, one kilogram of matter when throwing a stone while hunting. The fission reaction of heavy atomic nuclei is an extraordinarily powerful, controlled, and highly concentrated energy source. One kilogram of uranium or plutonium "replaces" thousands of tonnes of the best chemical fuel and the impact of 10^{13} cobblestones — a number exceeding the total stones ever thrown by all humans who have ever lived on Earth!

But physicists have something else in reserve. When a particle and an antiparticle meet, an annihilation reaction — "destruction" — occurs.

The electron and positron vanish, transforming into a quantum of energy. Here it is — the age-old dream of humanity: *the complete conversion of mass into energy!* The efficiency of utilising all the energy contained in matter is thousands of times greater than that of nuclear fission. But...

> "But for now, antimatter is far more expensive than the energy it would release upon combustion," says Corresponding Member of the USSR Academy of Sciences D. Blokhintsev. "However, it is not out of the question that it could be used as a concentrated fuel for space transport. But first, of course, we would need to overcome the challenges of storing and transporting antimatter, among other issues."

And if we let our imagination run free, we can envision the distant future of energy like this…

On an asteroid or an artificially created planet, energy is generated through a cycle of nuclear fusion reactions — the very process that powers our Sun and countless other similar stars. Meanwhile, on Earth, energy is drawn from controlled synthesis of elementary particles using free quarks, which we have learned to produce in unlimited quantities.

Wild fantasy? Today — yes. But here is what Academician B. Pontecorvo had to say about quarks:

> “If quarks exist, I have no doubt that they can be used. A stable ‘substance’ with entirely new properties will inevitably find practical applications.”

The same can be said about “magnetic matter” composed of Dirac monopoles — again, if they exist in nature.

And only fundamental research in high-energy physics and elementary particle physics can eliminate all these and many other “ifs.”

Universal Machines

Predicting the future has always been a difficult and thankless task. Reality has consistently proven to be far richer and more significant than imagined in forecasts. Subsequent generations have often been surprised by the lack of imagination shown by their predecessors.

It is difficult for us to understand how E. Rutherford could have doubted the possibility of any practical application of nuclear energy just a year or two before the discovery of nuclear fission.

However, the question of the present usefulness of particle physics can be considered not only in terms of vague promises but also in terms of concrete, real applications.

In 1950, an article by the renowned physicist and Nobel laureate E. Wigner was published in an American journal, containing the following line:

> "Our science increases our power much more successfully than it provides us with knowledge of purely human interest."

Now, more than twenty years later, it is impossible to agree with these words. Even if we set aside the discovery

of atomic energy sources, particle physics would still stand among the sciences beneficial to humanity, not empty-handed.

On the eve of the First International Conference on the Peaceful Uses of Atomic Energy in 1955, a session of the USSR Academy of Sciences was held, dedicated to the same issues. Even then, Academician A. Nesmeyanov stated that

> "the atomic industry provides science and technology with radioactive elements, whose radiation is used in medicine for treatment and diagnostics, as well as in the food industry, automation, defectoscopy, geological exploration, and many other fields. Chemistry and physics, metallurgy, the mechanics of gaseous, liquid, and solid bodies, and especially biology with its vast areas and directions — from the physiology of higher nervous activity to agronomy — have become broad fields for the application of labeled atoms, allowing for new working methods and leading to new discoveries."

But what new applications have emerged since then? And do the largest and most expensive devices in particle physics — accelerators — bring any tangible benefits to people?

When one of the first accelerators was being built in Dubna, the construction workers were surprised that no special railway track was laid for transporting the "products" that this massive machine would produce.

Cyclotrons, phasotrons... Wrapped in the mystical fog"

of science, they attract attention, as all things unknown and mysterious do. Visitors, often far removed from science, frequently come here on excursions. Most of them look at these massive iron structures with reverence and hesitation, feeling even more distanced from science as they observe its lifeless installations — symbols of modernity.

But are the complex structures of an oil refinery any more "human-friendly"? People simply know that kerosene and petrol are produced there. Even the enormous sums spent on landing humans on the Moon seem more justifiable than the expenses of high-energy physics research — this was the idea expressed by the well-known American physicist V. Weisskopf at the Tbilisi Symposium in 1969.

Unfortunately, even today, the general public remains largely unaware of the tremendous contributions that accelerators — and high-energy experimental physics as a whole — make to everyday life.

On the powerful synchrocyclotron built back in 1949 — during the difficult post-war years — the Institute for Nuclear Problems of the USSR Academy of Sciences studied the fission process of heavy nuclei under the influence of neutrons. These results were crucial for solving practical challenges related to the use of atomic energy. Today, accelerators of this kind are used not only by physicists but also by specialists from entirely different fields: radiochemists and medical professionals, radiobiologists and geochemists, as well as researchers from institutes directly connected to industry.

These facilities are used to test the radiation resistance of solar panels and to address the challenge of protecting humans from the effects of Earth's radiation belts and solar flares.

Advancements in accelerator technology have significantly propelled humanity forward in nuclear medicine and radiotherapy. More than half of all known radioactive nuclei were discovered in reactions studied on accelerators. While most isotopes are produced in nuclear reactors, the radioactive isotope zinc-72, which is used for the early detection of prostate cancer, can only be obtained using accelerators.

Doctors have long used cobalt-based radiation therapy to treat malignant tumours with gamma rays emitted by the radioactive isotope cobalt-60. However, this radiation also affects nearby healthy tissues. A more promising approach involves using protons and, especially, pi-mesons. When these particles stop within a substance, they release a large amount of energy in a very small volume, allowing for more precise targeting of tumours.

Physicists have already learned to create specialised "medical" proton beams at the synchrocyclotron in Dubna and the proton synchrotron in Moscow. Clinical oncologists from the Institute of Experimental and Clinical Oncology of the USSR Academy of Medical Sciences are now studying the possibility of using these beams to improve radiation therapy techniques for cancer treatment.

Thus, accelerators have already been quietly integrated

into human life.

So far, nothing has been said about the use of accelerators in industry. By using protons with an energy of about 150 MeV, the thickness of graphite can be measured with an accuracy of 0.0015%, compared to 2% when using alpha particles or electrons. Radiation treatment of materials in accelerators can increase their melting points, enhance tensile strength, improve durability, and alter the structure and properties of polymer materials.

At a national accelerator conference in Chicago, American physicist L. Rosen reported that out of 1,000 accelerators operating in the United States, fewer than 150 are used exclusively for fundamental research. About one-third are used in industry and medicine, while the rest are applied in various practical sciences.

Elementary particle physics indirectly influences the course of human technological progress.

> "As a truly advanced science," said Academician B. Pontecorvo, "it has either directly developed new methodological techniques for its own needs or stimulated their development. These advancements, often at the cutting edge of modern technology, have found practical applications in nuclear technology, medicine, biology, space exploration, mineral exploration, computing, and defence technologies. It is no coincidence that particle physics is now driving the development of superconducting magnets, which will undoubtedly have significant practical applications in various fields of technology."

For a long time, the cryogenic department at the Laboratory of High Energies at JINR worked on creating liquid hydrogen and deuterium targets for experiments with *K*-zero mesons. In the process, scientists developed specially designed "Dewars" that attracted the interest of many industrial organisations. More recently, representatives from the agricultural sector also visited. The head of the cryogenic department, A. Zeldovich, recalled how, while working on liquid hydrogen chambers, they also had to develop large-scale hydrogen liquefiers. These liquefiers were eventually mass-produced based on physicists' designs. For the first time in the USSR, they made it possible to obtain liquid para-hydrogen.

The Accelerator as an Energy Generator

Particle accelerators are widely used today. However, even with a vivid imagination, it is difficult to connect the word "accelerator" with "generator" — a device that produces energy. The contradiction in this phrase seems obvious. How can an accelerator be an energy generator when it continuously consumes significant amounts of energy itself?

Indeed, if the power supply is cut off, the massive machine immediately stops. There are no known cases where an accelerator has returned the energy spent on its operation, let alone produced energy.

Yet, despite this apparent contradiction, the idea in the

title is not fiction. It is not yet a reality, but it is a very real possibility. It turns out that a particle accelerator can be used to produce fuel for nuclear energy.

In 1955, the world's first nuclear power plant was launched in Obninsk, near Moscow, with a capacity of just 5 megawatts. Today, more than 230 nuclear power plants operate worldwide, generating a total of 20,000 megawatts. Currently, nuclear power accounts for only 2% of the world's energy supply. However, according to energy forecasts, this percentage is expected to rise to 30% by 1980 and reach 50% by the end of the century!

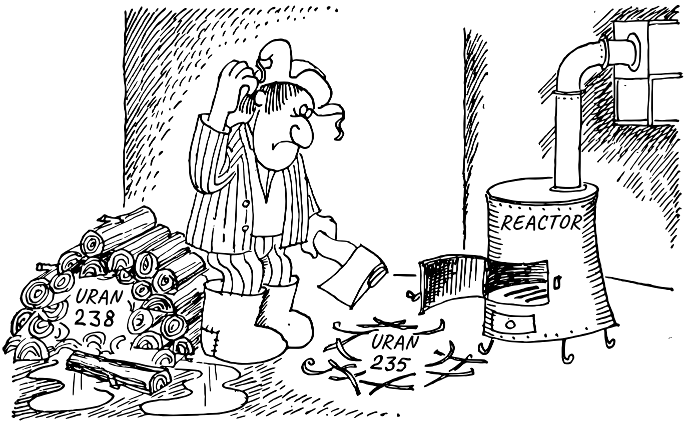
The time has come when atomic energy, once an unexpected discovery of microphysics, is transforming into a vital energy resource for the planet.

> "As one can easily see," says Academician N. Bogolyubov, "there have been radical changes in the relationship between 'the atom and society' from the First International Geneva Conference on the Peaceful Uses of Atomic Energy in 1955 to the Fourth in September 1971."

Indeed, what was once a concern only for scientists working on nuclear reactors now interests a much broader range of specialists. The United Nations General Assembly set a new and important goal for the Fourth Geneva Conference: it should be beneficial not only to scientists and engineers but also to industrial planners, administrators, and economists. Nuclear energy is becoming a necessity.

Now, let us return to the issue of nuclear fuel. What

do we mean by this term? Uranium? Yes, natural uranium serves as the fuel for nuclear power plants. But what does nature provide us? Only 0.7% of natural uranium consists of uranium-235 — the "dry kindling" that burns in a reactor. The rest is uranium-238, which is like "wet wood" that does not burn. If only we could use it, the available uranium reserves would last for hundreds of years. However, in thermal reactors, only a tiny fraction of it is consumed.



If we compare the current scale of uranium extraction with its "incomplete" combustion in reactors, the conclusion is discouraging. Despite the exceptionally high "calorific value" of uranium fuel, there is too little of it to sustain the nuclear energy of the future.

However, nature is not stingy. In addition to uranium-235, it has endowed plutonium-239 and uranium-233 with the ability to undergo fission, while at the same time de-

priving us of the possibility of obtaining them naturally — neither isotope exists in nature.

Nuclear physicists, however, know that plutonium can be produced from uranium-238 and uranium-233 from non-combustible natural thorium if they are irradiated with a powerful neutron flux.

At the Seventh World Energy Congress, Academician A. Alexandrov stated:

> "When we speak of practically inexhaustible nuclear fuel resources, we refer to the necessity and possibility of introducing secondary fuel — plutonium — and thereby utilising a greater portion of uranium-238 reserves. Without this, there can be no long-term development of nuclear energy on the scale dictated by the current pace of technological progress, as uranium-235 resources alone will be insufficient."

The known reserves of raw materials can only meet uranium demand until the late 1970s. Therefore, the task of establishing large-scale production of secondary fuel is already becoming urgent.

Plutonium can be produced if a vast number of neutrons is available. But where can they be obtained? This raises another challenge — the production of intense neutron fluxes.

A few neutrons are generated during nuclear fission in atomic reactors. Some of them are immediately absorbed to sustain the chain reaction, while others are captured by uranium-238 nuclei. From spent uranium fuel rods, a new

nuclear fuel — plutonium — is extracted.

This process is far more efficient in fast-neutron reactors. Around the reactor core, which operates on pure uranium-235 or plutonium, a layer of non-combustible "raw" uranium isotope or thorium is placed. By absorbing the fast neutrons emitted from the core, these materials transform into fissile substances.

However, the designers of such reactors still face numerous unresolved engineering and physical challenges. The reactors must be economically viable. More importantly, to sustain the necessary pace of nuclear energy development, the amount of plutonium produced in these reactors must double within a maximum of 5–7 years. Yet, all existing and under-construction fast-neutron reactors currently achieve this at a rate 2–4 times slower than required.

Physicists have therefore proposed an alternative method for producing fissile materials — one that does not rely on thermal or fast reactors but instead uses particle accelerators.

Atomic nuclei are true reservoirs packed with nucleons. But how to unlock them — that is the challenge. In nuclear reactors, neutrons are released through fission reactions. However, there is another approach.

At the beginning of the 20th century, using a primitive tool — an alpha-particle source — Ernest Rutherford was able to knock protons out of light nuclei for the first time.

But how much can be achieved by "picking at" the intricate lock of a nuclear vault with bare hands? Once scientists armed themselves with large-calibre tools — powerful particle accelerators — they succeeded in triggering the fission of heavy atomic nuclei. Accelerated protons shake up nuclei so heavily loaded with weakly bound nucleons that dozens of particles spill out simultaneously. A single high-energy proton can eject around 17 neutrons from a uranium nucleus and about 12 from a lead nucleus. The liberated particles possess considerable energy and, colliding with other nuclei, shake them up in turn. Thus, one by one, the "doors" of nuclear reservoirs are thrown open.

Fission reactions yield only a few neutrons from the nuclei of scarce fissile materials. However, if a piece of lead is placed in a powerful beam of protons from an accelerator, the lead becomes a neutron generator.

Now, if we replace the lead with a sufficiently large and dense target made of uranium-238 or thorium, the process intensifies. Once the accelerator is switched on, the reaction takes off — protons bombard the target nuclei, while the emitted neutrons "dry out" the non-combustible uranium. This method of producing secondary nuclear fuel has been named the *electronuclear process*.

The idea behind this method and its physical principles have been known for a long time. However, it could not be applied earlier due to the lack of a suitable accelerator. Today, physicists have a variety of options: cyclotron, phasotron, synchrophasotron... Yet, none of the existing

machines is suitable for this purpose.

The Serpukhov accelerator propels injected protons to 70,000 mega-electron volts. However, the number of particles it accelerates at the same time is relatively small – about 10^{12} protons per second. For industrial-scale neutron production using the electronuclear method, protons need to be given an energy of 1,000 MeV, but the accelerator must emit a million times more particles.

How can the magnetic field of the accelerator be made to collect, hold, and accelerate such an enormous number of protons? In a high-current accelerator, particles must be focused by the magnetic field even more rigidly than in the Serpukhov accelerator. But is it possible to simultaneously increase the density of the proton beam while maintaining a constant circulation frequency?

It seemed impossible to meet both of these requirements at once. But what would experiments show? And with what could experiments be conducted? Before constructing a complex and costly accelerator, one must be certain that it will function as intended.

Soviet scientists managed to break this vicious cycle. Under the leadership of Corresponding Member of the USSR Academy of Sciences V. Dzhelepov and Professor V. Dmitrievsky, they developed a model of a high-current proton cyclotron.

When people talk about creating a model of a new machine, they usually mean a scaled-down copy. But what

does it mean to create a model of an accelerator? A miniature accelerator, with all its dimensions reduced several times, would only be a mock-up, not a true model. A small magnet cannot accelerate protons to an energy of 1,000 MeV — yet the motion of particles must be simulated at precisely the speed they would have at that energy.

It is easy to say, "find a model for the proton." And yet, one was found: *the electron*! A full-fledged member of the world of elementary particles, the electron also has a single charge but is nearly a thousand times lighter than the proton. Electrons with an energy of just 0.5 MeV move at the same speed as heavy protons accelerated to 1,000 MeV, making them an excellent analogue for simulating proton motion in a magnetic field.

Using a small electronic model of the proton cyclotron, only two metres in diameter, scientists were able to determine the necessary magnetic field configuration. The model proved entirely viable. In early 1971, V. Dzhelepov, Director of the Laboratory of Nuclear Problems at the Joint Institute for Nuclear Research (JINR), announced:

> "Experiments on the electronic model have shown that it is possible to accelerate protons to energies of around 1,000 MeV while simultaneously producing 10^{18} particles per second! The power of such a beam will reach hundreds of megawatts. This paves the way for the creation of ultra-powerful meson factories, neutron generators, and more."

The term "meson factory" has become associated with accelerators designed for proton energies of no more than

1,000 MeV but with particle intensities several orders of magnitude higher than those of conventional machines. These facilities will be capable of producing powerful beams of pi- and mu-mesons. Such beams are essential not only for fundamental research but also for purely practical applications.

In our country, there are underdeveloped regions with abundant and inexpensive energy sources. For example, Eastern Siberia has vast reserves of hydroelectric power. Currently, the electricity generated by Siberian hydroelectric stations is transmitted over long high-voltage power lines into the national energy system, with significant losses along the way. A high-current accelerator with a target-reactor could, on-site, economically convert this cheap energy into nuclear fuel. The compact output of such a "factory" could then be easily transported to wherever it is needed.

It is impossible to predict when, where, and in what form such a facility for producing secondary nuclear fuel will be built. This depends on many factors: the further development of accelerator technology, the success of finding an optimal engineering solution for the target-reactor design, and whether the final installation will be economically viable.

However, one thing is clear: a new method for producing fissile materials has been proposed, based on a deep understanding of the behaviour of high-energy elementary particles.

Man-Made Atoms

In the summer of 1971, the town of Dubna near Moscow once again welcomed guests — participants of the Fourth International Conference on High-Energy Physics and Nuclear Structure. At one of the conference sessions, three Soviet scientists approached the podium one after another, presenting achievements in a new field of research that had emerged in Dubna — meson chemistry.

"The work of Soviet scientists in the field of mesochemistry is the best in the world. We would like to collaborate with them," said Professor L. Rosen from the United States during the conference.

Along the wall of the large synchrocyclotron hall at the Joint Institute for Nuclear Research (JINR), there is a series of openings — channels through which various particles from the accelerator are directed for experiments: protons, neutrons, and pi-mesons. In the areas where beams of mu-mesons pass, there are experimental setups designed to study key characteristics of chemical reactions using these particles. These setups closely resemble many other installations in the hall, containing a great deal of "physics" — elementary particle detectors and massive blocks of lead shielding — but nothing "chemical" — no flasks, test tubes, or distillation apparatus. Moreover, the chemist conducting the research has no direct contact with the studied substance. During accelerator operations, scientists remain several dozen meters away from the hall, monitoring the reactions occurring in the target material solely through

instrument readings.

How did this remarkable new method for studying the chemical properties of elements come about?

The Mu-Meson — one of the veterans of the elementary particle table — was discovered in cosmic rays in 1938, just a few years after Japanese theoretical physicist H. Yukawa predicted the existence of a light, unstable particle as the carrier of nuclear forces.

However, this particle, which quickly responded to the call of physicists, soon disappointed them: the mu-meson was unfit for the role it had been assigned. This raises a fundamental question — what is the role of this particle in nature, a particle that closely resembles the electron but has 200 times its mass?

A question posed thirty years ago remains unanswered to this day, despite being at the forefront of physics research.

> "Apparently," says Academician M. Markov, "one of the fundamental problems of modern elementary particle theory is understanding the differences in the physical properties of the mu-meson and the electron, as well as determining the place of the mu-meson and electron in the classification of elementary particles."

Since the 1950s, experimental physicists working with accelerators have thoroughly studied the properties of fast mesons and mesons that come to rest in matter. Yet, the enigmatic particle refused to reveal its secrets to scien-

tists. However, these very studies led to the emergence of mesochemistry.

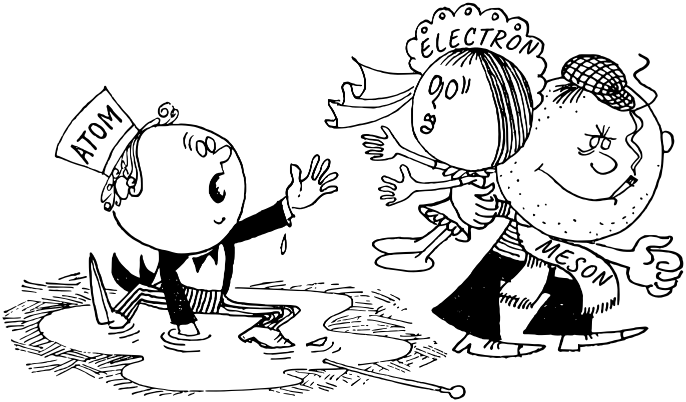
Mu-plus and mu-minus mesons are born from the decay of a heavier unstable particle — the pi-meson. They appear accompanied by neutrinos, and this remarkable particle always bestows some unusual property upon those who witness its creation.

Mu-mesons (muons) are no exception to this rule. The magnetic moments of all particles with the same charge sign have a strictly defined orientation. Such muons are said to be polarized. Physicists were astonished to discover that when these particles slow down and stop in matter, most of them lose their polarization within just a few millionths of a second — the brief time remaining before their decay. But why? What happens in the target placed in their path?

Measurements were conducted in different substances, yet the results defied interpretation. In some targets, less than half of the mesons lost their initial polarization, while in others, nearly all did. The polarization also varied depending on the temperature of the target material, its molecular structure, the presence of impurities, the strength of external magnetic fields, and many other external conditions.

One of the greatest Soviet theoretical physicists, L. Landau, was among the first to explain what happens to a mu-plus meson when it stops in matter. It turns out that the meson strips away a weakly bound outer electron from

a nearby atom and forms its own atom — an atom of *muonium*.



Muonium was discovered by experimental physicists, but one question remained: *what happens to it in the final millionths of a second before its decay?*

Muonium consists of a positively charged "nucleus" — a mu-plus meson — with a single orbiting negative electron. It closely resembles a hydrogen atom, except that it is lighter, as the meson is nine times less massive than a proton, the nucleus of a hydrogen atom. Moreover, muonium exists only until the mu-meson decays into two neutrinos and a positron. Yet, even in this fleeting moment, it does not go unnoticed by surrounding atoms.

In its chemical properties, muonium is the twin of the hydrogen atom, participating in the same chemical reactions. This means that in the final moments of its existence,

the mu-meson in muonium experiences an unusual fate for an elementary particle — a chemical one. This immediately affects the orientation of its magnetic moment.

Researchers at the Institute of Theoretical and Experimental Physics realized — and experimentally confirmed — that by tracking changes in the polarization of mu-mesons, one can precisely determine the absolute rate and type of muonium's chemical reactions, and consequently, those of hydrogen with other substances. Conventional chemical methods cannot achieve this level of precision, but the meson method faces no such limitation. A radioactive muonium atom, marked by the positron emitted during its decay, "reports" on the progress of a chemical reaction in solid, liquid, or gaseous samples. This eliminates the need for scientists to extract the final product of the chemical reaction from the studied material.

The fate of the mu-minus meson is different. As soon as it slows down in matter, an atomic nucleus immediately captures it into its orbit. The negative muon then takes the role of a "heavy" electron, giving rise to a mesoatom — a unique "isotope" of an existing element. Chemically, a mesoatom behaves like an atom of a naturally occurring element, but one positioned one place to the left in the periodic table relative to the element in which the negative meson came to rest.

A group of researchers from the Laboratory of Nuclear Problems at the Joint Institute for Nuclear Research (JINR) spent several years investigating why, under different con-

ditions, mu-mesons forming mesoatoms exhibit varying changes in the direction of their magnetic moments. After numerous experiments using an accelerator, physicists finally realized that they had become the first witnesses to a fascinating phenomenon — chemical reactions of mesoatoms!

In a water-filled target, oxygen atoms captured mu-minus mesons, transforming into mesoatoms resembling nitrogen atoms — models of atomic nitrogen. These models were not just theoretical but actively participating in reactions.

The meson-nitrogen atoms collided with other atoms, molecules, or molecular fragments in their environment, rapidly forming chemical compounds. Once again, the polarization of the mesons was disrupted, and sensitive instruments, detecting the electrons emitted from the target after meson decay, immediately recorded these changes. By tracking polarization disturbances, scientists could easily determine the course of the chemical reaction.

Hydrogen plays a crucial role in organic chemistry. Nearly 90 percent of all reactions in complex industrial processes, such as petroleum cracking, involve atomic hydrogen. If the absolute reaction rates of hydrogen were precisely known, it would be possible to use computers to precalculate the optimal conditions for any chemical industrial process.

As of now, this remains a distant dream. The fine-tuning of industrial chemistry still relies on trial and error,

a process that can take years or even decades.

Traditional chemical methods are incapable of isolating a specific reaction pathway. In practise, chemical reactions rarely proceed in a straightforward manner; they tend to develop a complex "web" of side reactions, varying across different experimental setups. As a result, absolute reaction rate values obtained by different researchers can differ significantly. The discrepancies are so large that chemists consider a hundredfold variation in reaction rates to be poor but tolerable, a tenfold difference to be acceptable, and a two- to threefold difference to be quite satisfactory.

Physicists studying elementary particles operate under entirely different conditions. Their methods are so precise that the results obtained are practically independent of experimental conditions. The same level of precision applies to the new meson method. Using mu-mesons, it is possible to determine the absolute rates of extremely fast chemical reactions between hydrogen and heavier atoms with various substances at different temperatures, with an accuracy of up to 10 percent.

Another substance that causes chemists significant challenges, second only to hydrogen, is nitrogen. Nitric acid is the backbone of the chemical industry, and large-scale chemical production is unimaginable without ammonia — just as spaceflight is impossible without hydrazine.

Despite nitrogen being a well-known element, the chemical properties of atomic nitrogen remain poorly understood, primarily due to its high chemical reactivity. This

reactivity makes it difficult to isolate reaction mechanisms and determine their quantitative characteristics, which are crucial for practical applications.

Now, *mesoatoms* offer a solution. By studying mesoatoms of nitrogen, scientists have obtained the first insights into the nature of chemical interactions between nitrogen atoms, hydrogen atoms, and hydrogen peroxide molecules. Using electronic detection equipment, they established that, in water and aqueous solutions at room temperature, meson-nitrogen undergoes chemical reactions in an incredibly short time — on the order of 10^{-11} seconds. They also succeeded in measuring the absolute rates of some of these reactions.

Of course, the scope extends far beyond just hydrogen and nitrogen. By selecting specific substances to slow down negatively charged mu-mesons, researchers can create "working" models of many other atoms and study their behaviour. Alternatively, mesoatoms can be used to investigate various processes occurring in the environment.

Dubna – The "Mecca" Of Mesochemistry

On nature's stage, in the plays titled *Chemistry* and *Physics*, the same performers take part. However, in traditional chemical processes, atoms and molecules are draped in elaborate "costumes" of intimidating compound names and bound by strict chemical conventions. As a result, it is as difficult to discern the physical essence of their

behaviour as it is to see an actor's true face in a masked theatre.

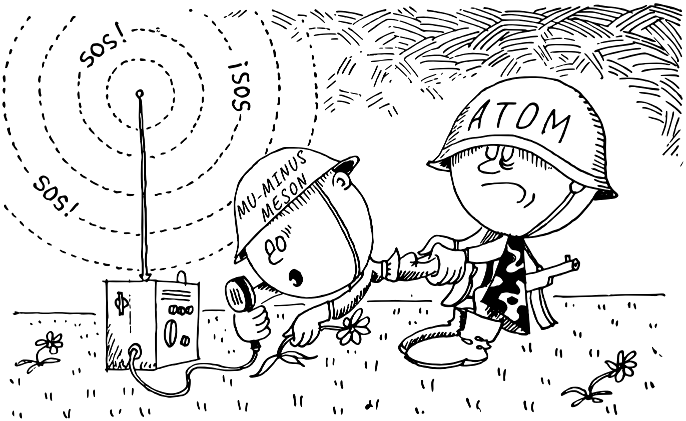
After developing the periodic table, Dmitri Mendeleev often expressed his desire to understand the reason behind the periodicity of chemical properties. Physics, by uncovering the structure of the atom, helped chemistry to understand itself — revealing the fundamental link between the structure of electron shells and the chemical properties of elements.

Yet, despite this progress, traditional methods of experimental chemistry do not always allow researchers to uncover this relationship in every specific case. As a result, experimentalists struggle to rely on theory, while theorists lack the necessary experimental data to verify their calculations. Even powerful computers offer little help, as the capabilities of theoretical chemistry remain limited.

Now, at the forefront of modern science, a "first-aid team" equipped with pi- and mu-mesons is emerging, following the path from elementary particle physics to chemistry.

Researchers at the Laboratory of Nuclear Problems made a groundbreaking discovery: the characteristics of X-ray radiation from mesoatoms reveal the chemical structure of the target material. By studying the oxides of various elements, physicists identified a clear periodicity in the properties of mesoatomic X-ray radiation. Had the periodic table not been discovered a century ago, it could have been predicted based on experiments with muons.

A mu-minus meson, upon entering an atom, emits a series of *X*-ray signals before being captured by the nucleus. These signals allow scientists to determine which atom has “imprisoned” the meson.



No matter how much you turn a box in your hands, if it’s tightly sealed, there’s no way to tell what’s inside. That is, unless you have a physicist working with a beam of mu-mesons. By bombarding the box with negatively charged mesons, they can instantly determine which chemical elements are inside — just by analyzing the *X*-ray radiation emitted from the material.

A thin beam of elementary particles, like the one produced at the Los Alamos “Meson Factory” in the U.S., can easily penetrate any internal organ of the human body. By comparing the radiation emitted by healthy tissue with that of diseased tissue, scientists could develop a powerful

tool for early medical diagnostics — an essential factor in successful treatment and recovery. This is yet another potential benefit of fundamental research into mesoatomic properties.

Another remarkable discovery was the influence of the electronic structure of hydrogen-containing compounds on the probability of nuclear reactions in which negatively charged pi-mesons are absorbed by protons. Pi-mesons have gained a second specialty: their ability to rapidly analyze the conditions of hydrogen atoms within complex molecules is unlocking new chemical mysteries.

For decades, scientists have debated the question: how do a solvent and the substance dissolved in it interact? Dmitri Mendeleev speculated that dissolution was not simply a mechanical breakdown into smaller and smaller particles, down to individual molecules, but a true chemical interaction. Yet, neither he nor the generations of chemists after him had the means to prove it — until now.

Not long ago, physicists directed a beam of pi-mesons from the synchrocyclotron at the Laboratory of Nuclear Problems at JINR onto a target filled first with distilled water and then with the same target containing an aqueous solution of a specific substance. The results were striking: in the second case, the probability of pi-meson capture changed, indicating a change in the electronic structure of water molecules. This provided direct evidence that water participates in a chemical reaction with the dissolved substance.

What is an acid? Even for specialists, providing a straightforward answer to this question is challenging. A monograph titled *Theoretical Inorganic Chemistry*, published in 1969, explicitly states: *"And yet, after three centuries of working with acids, there is still no unified definition of the concept of 'acid' or a comprehensive theory of its properties."*

What makes this so difficult? The main challenge lies in the lack of a clear definition of an acid's fundamental property — its strength. The idea that acid strength is likely related to molecular structure is not new to chemists. However, they previously lacked an appropriate tool to measure electron density in different regions of a molecule. Progress in this area remained stagnant — until physicists stepped in.

One by one, various acids were subjected to pi-meson probing. By analysing changes in the process of pi-meson capture by the hydrogen atoms within these acids, researchers determined the electron density distribution within their molecules. When the acids were arranged according to the obtained data, they fell into the exact order of decreasing strength. The meson "strength meter" had proven its reliability.

The meson-based method for studying substances represents a major scientific achievement in socialist countries. Mesochemistry is now experiencing rapid development, expanding beyond the walls of the Laboratory of Nuclear Problems. Today, Dubna is recognised worldwide

as a leading centre for mesochemical research, attracting scientists from many countries for training in this emerging field.

Advances in elementary particle physics have given rise to a powerful new branch of science, and soon, its branches will bear remarkable fruits.

Perhaps the time is not far off when comprehensive scientific complexes will be established. These would include high-current proton accelerators alongside institutes for physics and biology, facilities for secondary nuclear fuel production, industrial research institutes, hospitals, and other institutions. Naturally, such a complex would include a nuclear power plant, fueled by the accelerator itself and supplying the entire facility with nearly free energy.

8 A Small Universe

The Light Of The Universe Is Probably
As Complex
As Life On Earth
Still Remains Complex.

Yaroslav Smelyakov

A Laboratory For All

Above us stretches the boundless depth of an ever-changing sky. Sometimes it is covered with clouds and stormy formations; at other times, it displays shimmering shades of blue. Poets praise the sky, and landscape artists capture its beauty. Even physicists, who see it merely as the atmosphere, cannot help but find an element of scientific romance in it.

Along with the atmosphere, humanity has inherited a vast natural laboratory. Surprisingly, this realisation only

dawned upon us at the beginning of the 20th century, despite the concept of the atmosphere existing much earlier. Today, physicists understand that in the vacuum of interstellar space — just like inside the vacuum chambers of particle accelerators — protons, which make up 95 percent of primary cosmic radiation, race at nearly the speed of light. Upon reaching Earth's atmosphere, these protons collide with it. But what happens next?

Essentially, the same process occurs as in the Serpukhov accelerator when a beam of protons crashes into a target. However, in nature, this event is far more spectacular. Cosmic-ray protons, carrying enormous energy, smash into the atmosphere, shattering into a cascade of elementary particles that rain down upon Earth's surface.

Thus, our beautiful blue sky is nothing less than the target of a colossal cosmic proton accelerator. This natural accelerator holds records not only in terms of energy but also in the sheer number of elementary particles that have been discovered thanks to it.

Electrons, photons, protons, and neutrons — these are the particles discovered before the advent of accelerators and without the involvement of cosmic rays. However, the field of elementary particle physics was truly born only when the Wilson chamber first revealed the "products" of the cosmic accelerator: positrons, mu-mesons, pi-mesons, ka-mesons, hyperons...

In 1956, scientists finally succeeded in detecting the neutrino using a nuclear reactor. The writer G. Nikolaeva

responded to this event in her unfinished novel with these words:

> "I love the neutrino — predicted with hope, born with delight, christened with tenderness. I love the neutrino, that all-permeating little one, capable of piercing through the Galaxy with laughter, even if it were encased in concrete. I love the neutrino!"

Reflecting on the properties of weak interactions, scientists came to an unexpected conclusion: these enthusiastic words applied only to low-energy neutrinos, while high-energy neutrinos did not quite deserve such praise. But why? After all, all other elementary particles become more penetrating as their energy increases. Yet neutrinos behave differently!

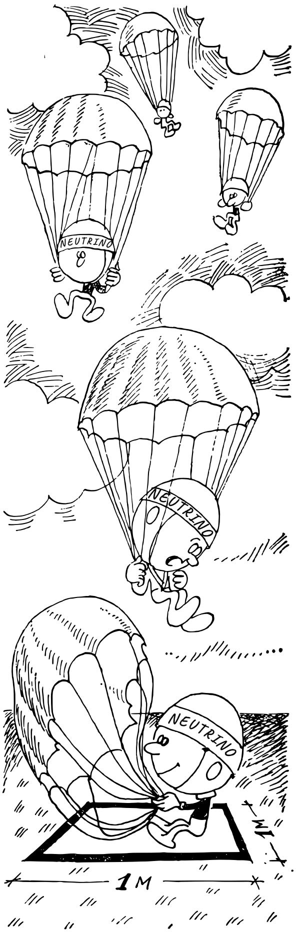
How could this hypothesis be tested experimentally? Where could scientists find neutrinos of sufficiently high energy?

Once again, cosmic rays provided the answer. Academician M. Markov proposed that neutrinos generated in Earth's atmosphere could be used to study weak interactions. Every square metre of Earth's surface is bombarded by thirty atmospheric neutrinos per second, each with an energy exceeding 10 billion electron volts!

This might seem like a vast number if one imagines neutrinos as raindrops. But it is an exceedingly small number when it comes to conducting specific experiments.

Do you recall how neutrinos were first detected? A small tank filled with scintillating liquid was exposed to an

incredibly intense flux of neutrinos from a nuclear reactor. But no one can compel the cosmic accelerator to produce more neutrinos at will. To reliably detect atmospheric neutrinos, an enormous tank would be required.



So, scientists devised an ingenious approach: *they conducted experiments in which the entire Earth itself played the role of a massive target in the weak stream of incoming neutrinos.*

Our Earth is transparent to neutrinos. Yet, one-millionth of their flux gets trapped in this massive target. When a neutrino interacts with Earth's matter, a light charged particle — a mu-meson — is produced, which can be detected using an ordinary counter. By registering these mu-mesons, scientists can study the interaction of high-energy neutrinos with matter.

However, there is a challenge. Cosmic accelerators also produce mu-mesons, and distinguishing them from those generated by neutrinos is impossible. What is the solution? The only way is to shield the experiment from these unwanted cosmic mu-mesons by placing an impenetrable barrier — three kilometres of Earth's crust — in their path.

In 1966, a massive experimental setup was assembled deep underground, over three kilometres beneath the surface in a gold mine near Johannesburg, South A — ca. It consisted of 36 five-metre-long detectors filled with 16 tonnes of special liquid. A hundred and fifty highly sensitive photo-multipliers continuously monitored the liquid, which scintillated when struck by elementary particles.

Over the course of a year, the setup successfully recorded ten atmospheric neutrinos.

A similar detection was made by another group of scientists at a depth of 2,300 metres in India. The results of these experiments, along with further tests conducted using particle accelerators, confirmed scientists' hypotheses.

In recent years, cosmic rays have once again taken centre stage. In the quest to develop a theory of elementary particles, the priority is not just the thorough study of known particles — which is, of course, more conveniently done using accelerators — but also the search for new ones: quarks, intermediate bosons, Dirac monopoles, and tests of fundamental theorems. And in this pursuit, energy is the decisive factor.

The "free" cosmotron is currently the only source of particles with energies that cannot yet be achieved artificially. Some scientists, such as Freeman Dyson, even believe that the future of high-energy physics lies not in building ever more powerful accelerators, but in constructing giant detection systems that operate using cosmic rays.

On the heaviest Soviet Earth satellites of the *Proton* series, special equipment and targets were installed to study the interaction of ultra-high-energy protons from primary cosmic radiation with matter. As the satellite passed through the atmosphere, it carried its targets and instruments into a stream of space-accelerated protons, much like how a target placed in an accelerator lock chamber is exposed to the proton beam at the Serpukhov accel-

erator. It is worth mentioning that satellites in the *Cosmos* series also carry detectors designed to register antiparticles and anti-nuclei in primary cosmic radiation.

We mentioned that mu-mesons are significantly heavier than electrons. This difference in mass may conceal one of the deepest mysteries of the microcosm. But is mass the only difference between them? And if not, what is the reason for the "heaviness" of the meson?

Theorists attempt to answer these questions by suggesting the existence of certain interactions specific to particular particles. The challenge for experimentalists is to find differences in the behaviour of muons and electrons. No differences have been observed in accelerator experiments — perhaps they only become apparent at extremely high energies?

At high-altitude research stations around the world, scientists carefully study the creation of mu-mesons by cosmic protons of enormous energy. Meanwhile, deep underground in mine shafts, researchers measure the angular distribution of mesons formed in the atmosphere.

Recently, these experiments have produced results that differ from theoretical predictions. These discrepancies have become the subject of intense debate.

A "Spoon" for the Sun

One day, people reappeared in an old abandoned mine in the state of South Dakota, USA. They did not look like miners, nor were they there to restore the disused mine or search for minerals. In 1968, Raymond Davis and a team of researchers assembled the first "telescope" at a depth of 1,500 metres — not to observe the stars, but to gather information about the Sun.

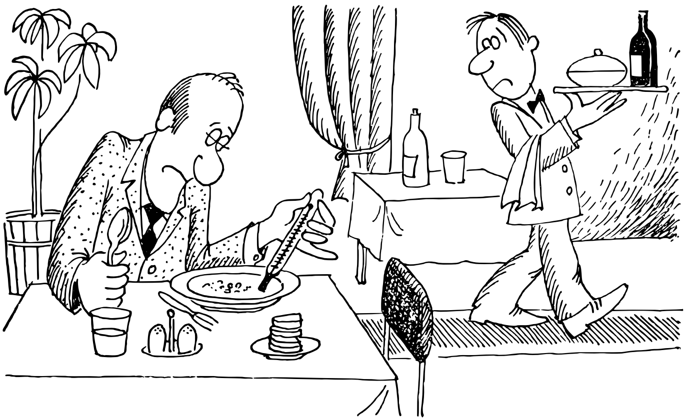
A telescope underground? But such instruments are usually placed on mountains, where the atmosphere is clearer. To avoid optical interference, they are sometimes lifted on balloons to the edge of Earth's atmosphere or even placed on satellites in space.

Davis' new instrument, however, was an entirely different kind of telescope. It was a massive cylindrical tank, six metres in diameter and fifteen metres long, filled with tetra-chloroethylene — a liquid containing chlorine. This device had no lenses or anything typically associated with an optical telescope. But then, an ordinary telescope cannot peer into the Sun's deep layers.

Photons are produced in the Sun's core, which occupies only a millionth of its total volume. To reach the surface, they must pass through an immense mass of matter. Naturally, they do not survive for long — each interaction causes them to give birth to new photons with lower energy. It takes millions of years for the distant descendants of these original particles to finally emerge at the Sun's surface, by

which time they "remember" nothing of their origins.

No matter how long you look at the surface of a soup, you can never tell whether it is thick or thin – you have to stir it with a spoon. Without a thermometer, you cannot determine its temperature either. Scientists who study the Sun using optical methods find themselves in a similar situation. They can analyse sunlight, which is mostly produced at the surface, but they have neither a "spoon" nor a "thermometer" to obtain information about its core.



Many questions have accumulated. So far, scientists only have a general understanding of what happens in the Sun's core. As early as 1920, A. Eddington proposed the hypothesis that the Sun derives its energy from thermonuclear reactions, in which light elements are transformed into heavier ones. But how can this hypothesis be confirmed? How can we determine which nuclear and

thermonuclear reactions take place there? What is the temperature and density of the Sun's core? It is only assumed that the core is significantly denser than lead and heated to 15 million degrees.

These questions would have remained unanswered if not for neutrinos. To probe the Sun, a particle was needed with an "un — endly," "uncommunicative" nature — one that possesses extraordinary penetrating ability because of these traits. Neutrinos are born in the Sun's core when hydrogen fuses into helium, releasing vast amounts of energy. Part of this energy is used to light and heat our planetary system.

If scientists' understanding of the Sun's energy source is correct, then Earth is constantly being bombarded by a veritable "Charcot shower" of solar neutrinos. One hundred billion of these particles should fall on every square centimetre of its surface every second!

But the most important thing is not this staggering number. The key fact is that neutrinos, once created in the Sun's core, travel in all directions without even noticing the enormous solar mass through which they move. They reach Earth in their "pristine state," carrying not only 10 percent of the Sun's total emitted energy but also invaluable information about its core.

It is a remarkable situation: sunlight does not provide scientists with answers to their pressing questions, while at the same time, the crucial information literally surrounds us in the form of solar neutrinos. If their intensity and

energy could be measured, scientists would have both a "spoon" and a "thermometer" to determine the temperature and density of the Sun's core.

This is the kind of neutrino telescope that American scientists built deep underground to study the Sun. A 1.5-kilometre layer of rock effectively shielded the instrument from cosmic rays and the mu-mesons that interfere with measurements, while at the same time allowing for an unobstructed "view" of the Sun using neutrinos.

R. Davis employed a method proposed in 1946 by B. Pontecorvo for detecting the then-unknown neutrino. In this "telescope," neutrinos colliding with chlorine atoms transform them into radioactive argon atoms. Special physico-chemical techniques make it possible to extract even a few argon atoms from a large volume of liquid. The rest is straightforward: the number of these radioactive argon atoms — essentially neutrino "traces" — can be easily counted using a standard particle detector.

But what was the outcome of this endeavour? There is no conclusion yet. In fact, this is not a story with an ending but one of the ongoing challenges in modern particle physics and astrophysics.

In the summer of 1972, an international conference on neutrino physics, "Neutrino-72," was held in Balatonfüred, Hungary.

> "It was no surprise," recalled participant B. Pontecorvo, "that the conference halls were packed at all times, despite the heat and the nearby cool waters of

> Lake Balaton. Among the attendees were the world’s leading experts in neutrino physics from the most prominent laboratories. Some of the conference reports caused a sensation — though, in my opinion, a premature one.”

The primary issue was a report by Professor R. Davis, who announced negative results in his attempts to detect solar neutrinos. Some scientists were even ready to declare the established understanding of thermonuclear energy generation in the Sun — and by extension, in other stars — incorrect.

According to B. Pontecorvo, such “revolutionary” conclusions are premature.

It is still reasonable to assume that the Sun derives its energy from the fusion of four protons into a helium nucleus. However, different cycles of nuclear reactions lead to this final process. R. Davis’ neutrino telescope is capable of detecting neutrinos from only a limited subset of these reactions.

The negative result may simply indicate that the Sun follows a different reaction cycle and that its temperature is 1 to 1.5 million degrees lower than previously estimated.

If the number of detected solar neutrinos turns out to be three or four times smaller, that would indeed be a paradigm shift in our understanding of how the Sun operates. For now, it is possible that neutrinos possess properties still unknown to us. For instance, they might decay before reaching the telescope or spontaneously transform

into anti-neutrinos on their way from the Sun to Earth — something R. Davis' instrument would be unable to detect.

Neutrino Tsunami

The Sun is a star that gives us life, warmth, and light. Sun worshippers have long expressed their gratitude to this ever-present miracle, elevating it to the status of a supreme deity — whether as Ra among the Egyptians or Yarilo among the Slavs. No wonder they were terrified of solar eclipses and offered prayers of thanks when the Sun, having "extinguished" in the evening, once again bathed the Earth in light each morning.

In reality, it was only in the early 20th century, following the discovery of the atomic nucleus, that a scientific explanation emerged for the source of the Sun's and other stars' energy. Humanity has yet to fully harness this form of energy. Even in the most advanced thermonuclear reactors, such as the *Tokamak*, hydrogen plasma still lacks the necessary temperature and density.

Ancient astronomers already observed changes occurring in stars. Historical chronicles and books contain records of extraordinary celestial events that we now recognise as novas and supernovae. Over time, the idea of stellar evolution took shape.

When hydrogen in the universe condensed into sufficiently dense clumps — the seeds of future stars — gravitational compression and simultaneous heating began.

Throughout a star's entire "life cycle," it existed under extreme pressure and temperature. Deep within massive, hot stars, conditions remained constantly favourable for elementary particle reactions.

Could scientists use this to uncover something crucial about the key stages of stellar evolution?

The thermal radiation energy of hot stars is so immense that within their depths, pairs of light particles — electrons and positrons — are constantly being created. When they collide, they annihilate each other, giving rise to thermal radiation photons once more. It might seem that this cycle, in which photons and electron-positron pairs exchange energy like a ball, could continue indefinitely. But it does not.

Once a star's temperature reaches hundreds of millions of degrees, a turning point occurs in its life. Some electron-positron pairs no longer transform into photons, as they did before, but instead into neutrino-antineutrino pairs, which immediately escape the star. By breaking the rules of the energy exchange game, neutrinos carry away the energy received from electron-positron pairs. There is no way for the star to reclaim this lost energy — it is gone forever.

The hotter a star becomes, the more neutrinos it emits. Neutrinos act like an open window in a room heated by a roaring fire. Everyone knows that to keep the room warm with an open window, more fuel must be added to the fire. Similarly, the star burns through its thermonuclear fuel at

an increasing rate.

Scientists believe that in the final centuries of a star's life, it loses most of its energy not as light but as neutrinos. A moment arrives when the star's energy reserves are completely "drained," leaving it with no way to replenish its loss — its hydrogen fuel is entirely "burned out."

But the star does not simply cool down. Instead, it consumes the gravitational energy of its own mass. This triggers a catastrophic and rapid collapse. Within mere fractions of a second, the star ejects an enormous number of neutrinos — far more than it emitted throughout its entire lifetime. Sometimes, a small portion of the star's matter is expelled at incredible speeds, creating an expanding cloud. This is when astronomers observe a supernova explosion — a brilliant flash from the ejected material. However, some stars collapse "quietly," without this dramatic "firework display."

If scientists can detect neutrino bursts from collapsing stars, we could gain insight into what happens at the very moment a star reaches the end of its evolution.

A neutrino wave from a supernova exploding in the centre of our galaxy could be recorded by a detector containing hundreds of tonnes of liquid. With several such detectors placed around the globe, the sequence of registered neutrino signals would reveal the exact source of the wave.

Supernova explosions in our galaxy are rare, occurring

roughly once every 300 years. But if "quiet" collapses truly exist, as some scientists suspect, then a neutrino tsunami could be striking Earth nearly once a month!

What happens if this powerful stream of stellar neutrinos, rushing at the speed of light, encounters a celestial body? A neutrino's rest mass is zero, but when moving at light speed, it gains inertial mass and becomes susceptible to gravitational forces.

A parallel beam of light falling on an optical lens is focused at a certain point. Similarly, the gravitational field of a randomly encountered cosmic body will focus a neutrino stream. The location where the neutrino "image" of a star appears depends solely on the radius and density of the cosmic body.

The Sun can also act as a gravitational lens. It will focus the neutrino image of a star at a distance of 100 billion kilometres from its centre — twenty times the radius of Pluto's orbit, the most distant planet in the Solar System.

The Earth, as it orbits the Sun, continuously focuses solar neutrinos as well. The neutrino image of the Sun, following Earth's movement, shifts through space to a distance of one trillion kilometres from Earth's centre. All that remains is to place a "film" at this location to capture an image of the star as seen through the "eyes" of neutrinos.

Unfortunately, no such film exists for this cosmic "camera," nor does the camera itself. However, Soviet scientist I. Lapides proposed that the focusing properties of massive

celestial bodies could be used to “construct” a neutrino telescope for detecting sources of neutrino radiation.

For example, a large spacecraft equipped with a neutrino detector, well shielded from cosmic rays, could be placed in a solar orbit with a radius equal to the Sun’s neutrino focal distance. As the spacecraft moves along the surface of a sphere at this radius, its instruments would scan the regions of space located beyond the Sun. The moment a neutrino-emitting star aligns with the line connecting the spacecraft to the Sun’s centre, the detector would register a sharp increase in the flow of these particles.

A spacecraft propelled by hydrogen bomb explosions, a concept in which F. Dyson was involved, would be suitable for this purpose. He believes that a spacecraft with a payload capacity of tens or even hundreds of thousands of tonnes — precisely the kind needed to carry a neutrino detector with proper shielding — could be built today with the current level of science and technology. However, the cost of such a spacecraft remains so high that its construction is currently beyond the reach of even the most developed nations.

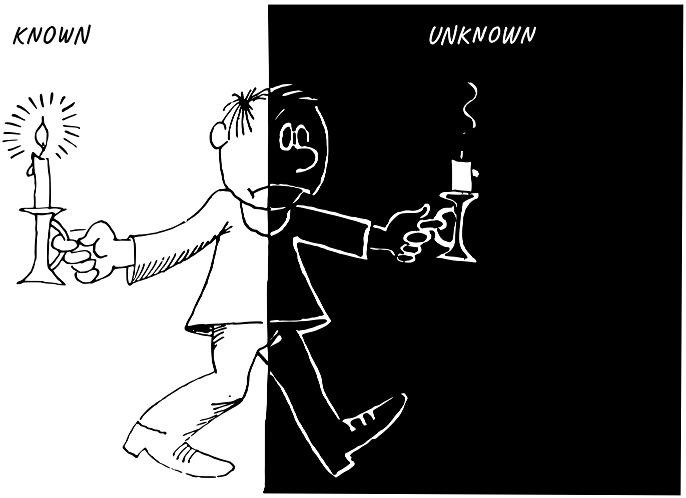
Peers Of The Universe

We do not know what is happening on the Sun at this very moment. Only in eight minutes will light rays or solar neutrinos inform us that the Sun is functioning normally.

The last signal from a collapsing star at the edge of the

Galaxy will reach us thousands of years later as a powerful burst of neutrino waves or a "spasm" of the gravitational field. No matter how long the journey of these messengers of distant events, we will recognise the voice of the universe we already know.

But what was it like billions of years ago? This is the "question of questions" in cosmology, which, according to Academician V. Ginzburg, "belongs to the very few scientific fields (another such field being elementary particle physics) where we encounter the deepest fundamental questions. Here lies the boundary between the light of knowledge and the absolute darkness of the unknown."



In 1929, E. Hubble discovered that galaxies are receding in all directions at a constant speed, like fragments of an ex-

ploding bomb. If one mentally rewinds the imaginary film recording this phenomenon at the same speed, it turns out that the age of the universe — from the moment its density was infinitely great to its present state — is quite respectable, about 10 billion years. But how did the "history" of the universe unfold?

Archaeological discoveries allow us to form an idea of Earth's earliest civilisations and learn about events that took place around 30,000 years ago. Palaeontology tells us about the oldest forms of life and the evolution of the organic world, reconstructing it from skeletal fragments, fossils, and imprints. Palaeontologists seem to embark on a journey through time, stretching back a billion years.

But what kind of discoveries can one expect when dealing with a time-span as vast as ten billion years? This led to a theoretical debate among scientists. Some favoured the idea proposed in the 1940s by the renowned theoretical physicist G. Gamow — the "hot" model of the universe's evolution. He believed that if there was a time when its density exceeded a tonne per cubic centimetre, the temperature of matter must have been extremely high. Others supported the idea of a "cold" model of the universe's development.

For a long time, the debate remained fruitless — neither side could present experimental evidence. Then, unexpectedly, a discovery was made that strongly reinforced the case for the "hot" model.

Thirty years ago, astrophysicists were studying the opti-

cal properties of cyanogen molecules in interstellar galactic gas. In the process, they detected electromagnetic radiation in space with a wavelength of 0.25 centimetres. These radio waves came from all directions in the cosmos with an intensity 100,000 times greater than that of similar radiation from all known celestial sources. The discovery was made, noted with amazement, and... that was all. Strangely, no one even attempted to determine its origin.

In 1965, researchers at Bell Telephone Laboratories — A. Penzias and R. Wilson — were developing a satellite communication system operating at a wavelength of 7.3 centimetres. For the equipment to function properly, it was necessary to investigate all interference at that wavelength. And when it seemed that they had eliminated every possible source of radio noise, their exceptionally precise instruments continued to register very intense radiation arriving uniformly from all directions.

Thus — already for the second time — the *cosmic microwave background radiation* [CMBR] was discovered, a *relic* from long past eras.

What have these radio waves not experienced since those ancient times! On their journey to Earth, they were scattered countless times by interstellar matter, gradually losing memory of their original state. Finally, as the universe expanded, they cooled to a temperature of about 3° Kelvin.

Even these "forgetful" witnesses are a valuable discovery for scientists. The energy of each quantum of this

thermal radiation is two thousand times lower than that of a visible light photon. Yet there are so many of them that for every atom in the universe there are about one hundred million relic quanta. This abundance gives scientists the opportunity to perform precise experiments to glean information about the nature of the universe's expansion.

But can we learn what happened even earlier? What was the universe like in the very first minutes and seconds of its existence?

The equations of mechanics and the "cooling" law for relic radiation quanta have enabled scientists to embark on a journey into such depths of time that even the most intrepid hero of a science fiction novel has never ventured.

Ten billion years ago, the universe bore little resemblance to what we now understand by that word. There were no stars, no galaxies. Instead, there was only an ultra-dense, scorching-hot mass of matter, composed of individual elementary particles mixed with radiation.

As the universe expanded, the temperature of this radiation gradually decreased until the moment came when it ceased to influence matter. Left to its own course in cosmic space, the relic radiation has "survived" to the present day.

But that is not all. During the so-called "lepton era," when the universe was only fractions of a second old, light particles — leptons (muons, electrons, neutrinos, and antineutrinos) — played the dominant role. However, reac-

tions involving these particles quickly ended, and neutrinos became free.

What fascinating stories these "living" contemporaries of the newborn universe could tell! Relic neutrinos could help scientists reconstruct a picture of the just-born world. These witnesses possess phenomenal "memory" due to their weak interaction with matter. If they could be detected, it would allow for a definitive answer about the conditions that prevailed in the universe during its first seconds and minutes of existence.

> "The search for relic neutrinos, no matter how difficult it may be," says Academician Ya. Zeldovich, "is extremely important for understanding the earliest stages of cosmological expansion. Indeed, measuring relic neutrinos will be the 'experiment of the century.' "

Antiworlds?

When did this word first appear? It is known for certain that the poet Andrei Voznesensky was not the first person to use it. However, thanks to him, we have the opportunity to read the word *antiworlds* in an affirmative tone, printed in large letters on posters of the Moscow Taganka Theatre.

But who actually said "A"? Consider the logical genesis of this word:

$$\text{antiparticles} \quad \rightarrow \quad \text{antimatter} \quad \rightarrow \quad \text{antiworld.}$$

Clearly, it was physicists — who discovered anti-particles

— who first uttered it. First came the positron, then the anti-proton, and others.

In Novosibirsk, scientists were the first to obtain a "piece" of antimatter — a beam of positrons that existed for hours. "This was already something almost real and tangible not only for physicists but for anyone. Please, look — here it is, the light of antiparticles!" said Academician G. Budker, director of the Novosibirsk Institute of Nuclear Physics.

But anti-particles alone do not make anti-matter. Ordinary matter consists of atoms, and atoms consist of atomic nuclei and electrons. All the components of antimatter — anti-protons, anti-neutrons, and positrons — were discovered experimentally. But one question remained: *could nuclear forces "glue" antiparticles together into anti-nuclei?*

Theoreticians had no doubts about this. Their equations indicated that, along with antiparticles, anti-nuclei composed of anti-protons and anti-neutrons must also exist. Nothing prevented one from imagining an anti-world in which all chemical elements were anti-elements, filling an *anti-Mendeleev's* table. In terms of chemical diversity, this world would be no less rich than our own.

At a 30 mega-electron-volt accelerator in Brookhaven, USA, experimentalists managed to realise the theorists' dream.

Instruments recorded the birth of anti-deuterium nuclei — the heavy isotope of hydrogen. An anti-proton and an anti-neutron had joined together to form an anti-

nucleus!

The next element in the periodic table is helium. But what if antiparticles cannot form nuclei heavier than deuterium? To investigate this, an accelerator with an energy of 70 mega-electron-volts was required.

A large team of scientists, led by Corresponding Member of the USSR Academy of Sciences Y. Prokoshkin, began an experiment at the Serpukhov accelerator to search for anti-helium nuclei. After analysing more than 200 billion particles, the experimenters identified five anti-helium nuclei among them.

The complexity of this achievement was well illustrated by Academician A. Logunov, director of the Institute for High Energy Physics:

> "If we wished to graphically depict the total number of particles that passed through the setup in relation to the number of registered anti-helium nuclei and represented the number of anti-helium nuclei as a one-millimetre-long segment, then the number of other particles would have to be shown as a segment equal in length to the Earth's equator."

The discovery of anti-helium nuclei confirms the theory of antimatter's existence. And the presence of antimatter could be of immense significance for understanding the evolution of the universe and the processes occurring within it.

Particles and antiparticles annihilate upon collision — "exploding" with the release of enormous energy. Because

of this reaction, antimatter cannot coexist with ordinary matter. Astrophysicists have therefore used the hypothesis of "anti-worlds" to explain the powerful sources of radiation discovered in the universe.

Elementary particles and radiation are the common ancestors of all stars and galaxies. And if we attempt to solve cosmological problems based on knowledge of elementary particles gained through accelerators, we must first recall the law of baryon number conservation. This law states that protons and neutrons are always created in pairs with their anti-particles. In other words, matter is always born in the same location and in the same quantities as antimatter. It was thus natural to assume that the "primordial" plasma consisted of equal numbers of particles and anti-particles.

Scientists have long confirmed that the solar system consists solely of matter. Moreover, if matter and antimatter were mixed within our galaxy, instruments on Earth would continuously detect powerful annihilation radiation. Yet such radiation is absent.

So, does antimatter *exist* somewhere in the universe?

The answers one hears today are diametrically opposed. "Antimatter does not exist; it is merely the subject of speculation by overly enthusiastic dreamers," say some. They believe that the universe, from the very first moments of its existence, was already asymmetrical — there was more matter than antimatter.

"Antimatter in the universe may be just as abundant as matter," others argue, "since there is no proof that it does not exist."

Let us ask a different question: *if antimatter does exist in the universe, then where is it? Why does it not reveal itself in any way?*

Renowned Swedish scientists H. Alfvén and F. Klein suggest that matter and antimatter were separated by electromagnetic fields during the early stages of the universe's evolution. It is therefore possible that every second star or galaxy is composed of antimatter.

> "For some reason, it is easier to believe," writes honorary member of the USSR Academy of Sciences, Professor H. Alfvén, in his book *Worlds and Antiworlds*, "that some distant galaxy is made of antimatter. The prospect of a dangerously close antistar would be far too unsettling. However, analysis leads us to the opposite conclusion: it is much harder to justify the separation of matter on a galactic scale than within relatively small regions inside each galaxy."

The discovery of relic thermal radiation confirmed the validity of the "hot" model of the universe's development. However, the question of antimatter remained just as challenging. There was still no sufficiently justified mechanism for the separation of matter and antimatter at the very earliest stage.

Just a few years ago, the French scientist R. Omnés pro-

posed an original hypothesis for the separation of matter and antimatter within the framework of the "hot" model. The behaviour of protons and anti-protons, well studied in laboratory accelerators, led him to the idea of a separation mechanism resembling the formation of liquid droplets in a supersaturated vapour. Moreover, if the properties of these particles were different, the separation could no longer be explained.

In less than 10^{-5} seconds, the initially homogeneous plasma would form something akin to an "emulsion" of separate regions filled with particles and antiparticles. From there, the process follows the Alfvén-Klein theory: identical regions merge upon collision, while those with opposite baryonic charges repel each other due to the pressure of annihilation radiation. Gradually, they drift apart over vast cosmic distances.

Theoretical debates between proponents of a charge-symmetric and an asymmetric universe continue. However, the final answer will, of course, come from experiments.

Does the light from a star differ from that of an anti-star? How can one distinguish between a world and an anti-world? It is entirely possible that before astronomers' very eyes, the spirals and "arms" of anti-galaxies unfold, and anti-stars twinkle. However, the electromagnetic radiation of matter and antimatter appears completely identical to the naked eye. But has this been experimentally verified?

Not yet. But here is what Academician G. Budker dreams

of:

> "We want to try to create not just antiparticles in the laboratory, but antiatoms. We hope to obtain a sufficiently noticeable stream of antihydrogen capable, for instance, of burning through a sheet of paper. This would allow us to study the properties of antihydrogen, particularly its spectrum. Right now, astrophysicists are debating whether antigalaxies exist in the universe and whether matter and antimatter are equally represented. Perhaps our experiments will serve as the 'judge' in this dispute."

In principle, this debate could be resolved with neutrinos. A star made of antimatter or an anti-galaxy should emit anti-neutrino streams instead of neutrinos. It is quite possible that they reach the Earth's surface. However, neutrino astronomy is powerless in this case. Even from the brightest stars like Sirius, only about one neutrino or antineutrino per square centimetre reaches Earth every second.

A more realistic approach to detecting antimatter in the universe is through cosmic rays originating beyond the solar system. It is assumed that individual antiparticles can emerge from collisions between high-energy cosmic particles and interstellar gas. However, the likelihood of forming complex anti-nuclei is almost zero. If they are ever detected, it would confirm the existence of distant anti-worlds, from which these fully formed anti-nuclei originate.

So far, neither anti-protons nor anti-nuclei have been

found in cosmic rays. But the precision of experiments continues to improve, and perhaps the time will come when scientists can decipher the information about antimatter in the universe contained within cosmic rays.

In the 1960s, Academician B. Konstantinov proposed the hypothesis that if anti-worlds exist, then sufficiently large bodies of antimatter should occasionally reach Earth.

Astronomers know that not all comets and meteors follow elliptical orbits and are, so to speak, “assigned” to the solar system. Some of them arrive from very distant regions of the galaxy, only to either burn up in Earth’s atmosphere or disappear forever into the vastness of space. Could some of these be messengers from anti-worlds?

The story of the Tunguska meteorite is well known. It exploded in 1908 over the Podkamennaya Tunguska region at an altitude of 5 to 10 kilometres above the Earth’s surface. The explosion’s power was enormous — about 10^{24} ergs. Many theories have been proposed to explain this event, including the more romantic hypothesis of an alien spacecraft explosion.

But there is another, more natural, more plausible, and no less fascinating idea. Could the Tunguska meteorite have been a chunk of antimatter that accidentally entered Earth’s atmosphere?

An explosion similar to that of an atomic or hydrogen bomb in the atmosphere requires special conditions — conditions that can only be created by an intelligent be-

ing. However, an annihilation explosion requires only the presence of antimatter itself.

In such an explosion, the amount of radioactive carbon nuclei in the atmosphere should increase. The only witnesses to this would be carbon-absorbing trees that lived at the time of the Tunguska event. Unfortunately, studies of the radioactive content in the annual growth rings of old trees from 1909 have shown only a one percent increase in carbon-14 isotope levels compared to the average over forty years. This figure falls within the margin of measurement accuracy.

The results have neither confirmed nor definitively disproved the anti-meteorite hypothesis. As scientists say, the question remains open.

The Moon, which has now become a direct subject of experimental research by Soviet and American scientists, may also help in solving the problem of the existence of matter and antimatter in nature. Since our satellite has no atmosphere, if anti-meteorites had ever impacted its surface, their annihilation should have left behind radioactive spots with an elevated concentration of long-lived elements such as aluminum-26.

Academician B. Konstantinov was particularly interested in comets — unusual celestial bodies that, despite their small size (within ten kilometres), possess long tails stretching hundreds of kilometres. The usual explanation is that comets consist of icy masses. But could some comets actually be anti-asteroids that entered the solar

system from an antiworld?

This hypothesis led to yet another method for detecting antimatter. Comets eventually disintegrate, turning into meteor streams. However, if meteors composed of antimatter were to enter Earth's atmosphere, their annihilation should produce gamma rays with specific energy signatures.

A team of scientists from the Leningrad Physical-Technical Institute, led by Professor M. Bredov, has been experimentally studying the symmetry of matter and antimatter in nature for several years. Using radar methods, they record the exact moment a meteor enters the atmosphere while simultaneously monitoring whether there is an increase in radiation intensity characteristic of annihilation.

Over four years, all major meteor streams were investigated, and the results were encouraging. The entry of meteors into the atmosphere was accompanied by an increase in specific radiation.

Other experiments were also conducted. Instruments capable of detecting gamma rays of a strictly defined energy — those produced in electron-positron interactions — were placed aboard an artificial Earth satellite. It was observed that the number of gamma rays varied depending on meteor activity.

The increase in radiation intensity, confirmed by two independent methods, appears to be a reliably established fact.

> "The question of the universe's symmetry," said Professor M. Bredov, "has now become pressing not only in theoretical discussions but also in experimental studies, as the evidence seems to support our hypothesis. However, we do not dare to say a decisive 'yes' where much remains unclear. There are still many challenges. The problem is highly controversial, and perhaps that is precisely what makes it so fascinating."

The stellar world that astronomers of the past observed through the narrow window of visible light seemed fixed and unchanging. The life of the cosmos was thought to be disturbed only on the rare occasions when a supernova flared up.

Now, however, radio waves, *X*-rays, infrared radiation, and gamma rays have revealed an entirely different universe. Static images have come to life. Astrophysicists are now witnessing an enthralling, ever-changing film of the turbulent life of the metagalaxy.

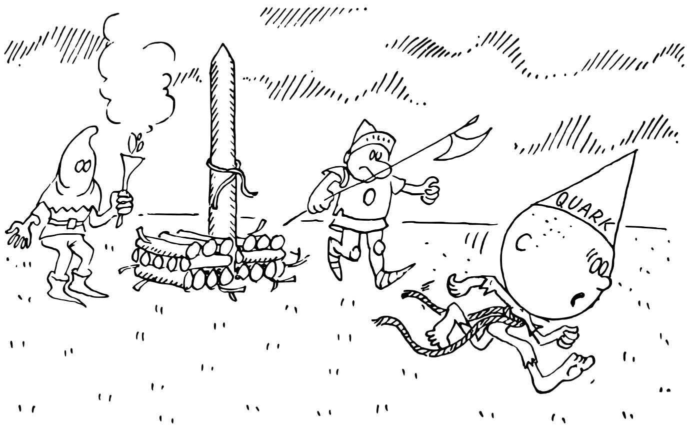
Events unfold at a rapid pace, even by earthly standards of time. While a supernova explosion lasts about a hundred days, the emission period of the fastest pulsar is just 0.033 seconds! Stars heat up, cool down, and condense, scattering showers of elementary particles into space. Stellar associations are born, quasars and explosive stars release colossal energy.

"As they say, the entire universe itself is but an unfinished, ongoing explosion," writes the poet L. Martynov in

his poem *Harmony of the Spheres*.

While probing the depths of matter, physicists have discovered a world of elementary particles, which, according to the "hot" model, closely resembled the ultra-dense and incandescent mixture that constituted the early universe. Could this model now help resolve some outstanding problems in elementary particle physics?

Theorists have conceived quarks, yet experimentalists have failed to find them. Dirac's magnetic monopoles are needed to restore symmetry to Maxwell's equations and quantum electrodynamics, but no one has ever seen them. Hunters of quarks and those in pursuit of magnetic monopoles have returned empty-handed. They have not been found in cosmic rays, on the ocean floor, or in mountain rocks. Why?



Of course, one could simply answer: *because neither*

quarks nor monopoles exist. But what if they do? Can we at least roughly estimate how many of them exist in nature? For example, quarks?

Soviet theoretical physicists Ya. Zeldovich, Ya. Okun, and S. Pikelner attempted to trace the fate of free, relic quarks as real particles, based on the “hot” model of the universe.

In the beginning, when the radiation temperature was extremely high, pairs of all kinds of particles, including quarks, were born. However, the immense density of matter compressed their lifespans into mere instants. As soon as they emerged, they immediately annihilated each other, disappearing into radiation.

As some of the heaviest particles, quarks were likely among the first to feel the changing climate of the universe. As the universe cooled, conditions arose similar to those in modern particle accelerators, where there was no longer enough energy to create quarks. The universe expanded, and the density of its matter decreased. It became increasingly difficult for quarks and anti-quarks to find each other, and the annihilation processes ceased.

Quarks that survived this “burnout” could have persisted to the present day. However, their numbers depended on the development history of the region of the universe closest to us. If these regions were extremely hot, annihilation processes could have destroyed a significant number of quarks. This uncertainty makes any answer somewhat indeterminate. However, the conclusion that

only about 10^{-10} to 10^{-13} quarks per nucleon might exist in nature provided some relief to "hunters" of these exotic particles.

And what can the theory of cosmic evolution say about the existence of Dirac monopoles in nature?

Scientists working within the "hot" model of the universe estimated the possible concentration of "relic" magnetic charges. As with quarks, at a certain stage in the universe's evolution, the annihilation of monopoles and anti-monopoles ceased due to the insufficient density of these particles.

How many of these particles have survived to the present day? The answer is discouraging: only 10^{-13} particles per square centimetre per second. Detecting particles that exist in such minuscule quantities is no easy task. This conclusion provided some reassurance to experimental physicists, justifying their negative results.

Recent advances in cosmology have radically altered our view of the universe's life. The so-called cosmic "void" now gives way to a sense of density. There are 400 relic thermal quanta per cubic centimetre of space!

At unknown cosmic crossroads, streams of elementary particles ejected by stars surely encounter the "eternal wanderers" — the relic thermal quanta and neutrinos that fill the vastness of space. Could it be due to the " — ction" between cosmic particles and relic quanta that the maximum energy of cosmic rays reaching Earth's atmosphere

does not exceed 10^{19}–10^{20} electron volts?

"The problems of the vast universe are closely intertwined with the challenges of elementary particle theory," said Academician V. Ambartsumian.

> "How do ultra-high-energy particles behave as they pass through the rarefied interstellar medium and cosmic magnetic fields? Are there antiparticles in cosmic rays, and in what quantity? What type of elementary particles is the main carrier of the enormous energy concentrated in radio galaxies and gradually emitted as radio waves? Naturally, many astrophysicists link the possibility of theoretically solving the problem of the origin of stars and galaxies to future advancements in elementary particle physics."

The Small Universe

At the end of the 16th century, the task of constructing a unified picture of the world was set for the first time. Johannes Kepler attempted to unite two seemingly unrelated domains — those of the earthly and the celestial — under the concept of the "universe."

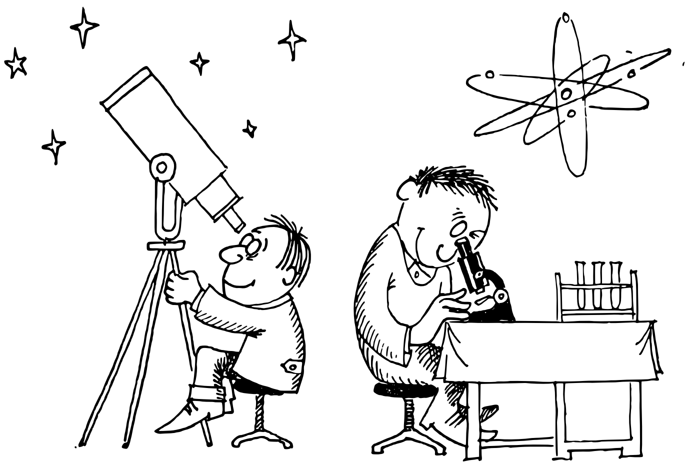
This effort evoked an emotional response from the English poet John Donne, a contemporary of Kepler:

> From parallels and meridians
> Man wove a net and cast it wide,
> Over the heavens — and now they are his domain.

Thus he wrote in 1611 in his poem *An Anatomy of the*

World.

Much water has flowed under the bridge since then. Many changes have taken place in the world. The army of natural scientists long ago split into separate divisions — some delving ever deeper into the structure of matter, others striving to uncover the mysteries of the cosmos. It seemed as though they were moving in opposite directions and that the connection between the structure of space, explored down to scales of 10^{-15} centimetres, and the processes occurring within the visible universe, extending to 10^{28} centimetres, was becoming less apparent.



In reality, however, the idea of the material unity of the world is now clearer than ever before, uniting our understanding of the infinitely large and the infinitesimally small. All our conceptions of the vast cosmos rest upon the same

principles that govern the laws of the micro-world.

"No matter how remarkable the latest astronomical discoveries may be, they have not yet taken us beyond the known physical concepts and laws," writes Academician V. Ginzburg.

What, then, do particle physicists expect from astrophysicists and astronomers?

Today, the sum of all our knowledge about the micro-world is still unable to illuminate the darkness of the unknown that shrouds the first moments of the universe's existence. The physical laws known to us cease to function at densities greater than 10^{93} g/cm³. But perhaps it is precisely in these *initial conditions* that the secrets of new, yet undiscovered interactions governing the world of elementary particles are hidden.

> "In that case," Freeman Dyson once remarked, "we cannot expect any final clarification in particle physics until observational evidence provides answers to the great, still completely open questions of cosmology."

Weak interactions between elementary particles have overturned the principles of charge and spatial symmetry. But is this violation somehow linked to the asymmetry of the macroscopic universe? Or perhaps to the absence of antimatter in the cosmos? Once again, the answer seems to be concealed within the *initial conditions* of the universe's birth. It was from these same conditions that the "arrow of time" began its relentless flight — an arrow now being

sought in the micro-world.

And what about the problems of gravity? Particle physics has reached the point where the role of gravitational interaction must be accounted for in the development of elementary particle theory. In recent years, Academician M. Markov has been working on a model in which the structure of elementary particles is determined by the gravitational interaction of massive cosmic-scale objects. In honor of Soviet theoretical physicist A. — edmann — who derived groundbreaking cosmological consequences from the theory of relativity — Markov named his proposed elementary particle model the *— edmon*. Markov's *— edmon Theory* represents the first attempt to construct an extended model of an elementary particle not based on quantum mechanics, but within the framework of a cosmological approach.

> "The theory of — edmons," writes Academician M. Markov, "allows us to consider universes as elementary particles and elementary particles as universes, which, despite their external identity, may possess the most diverse internal structures."

One might think these lines come from a work of science fiction rather than an article by a world-renowned scientist.

> "The very possibility of such a unification of opposing properties," Markov continues, "the properties of the ultra-large and the ultra-small, appears no less astonishing than the unification of corpuscular and wave properties within a single object."

Markov's theory presents an intriguing opportunity for expanding our worldview regarding the structure of matter.

What awaits us in this regard, for instance, in the quantum unified field theory currently being developed by Werner Heisenberg? The fundamental essence of all matter — what he calls *primordial matter* — is conceived as a single unified field.

> "With the completion of my theory," Heisenberg writes, "physics will no longer probe deeper, but rather expand outward."

What about another approach to the structure of matter, one rooted in the traditional idea of *consists of …*?

The emergence of the idea that pi-mesons might be composed of nucleons and anti-nucleons, and that nucleons, in turn, consist of quarks — that is, the notion that elementary particles themselves may be made up of even heavier entities — was described by Academician M. Markov as "perhaps the most striking and significant event in the entire thousand-year history of our understanding of matter."

But can the quark form of matter be equated with primordial matter? Or should we assume that quarks themselves are composed of even heavier particles? But then, would the *most elementary* particle have infinite mass?

> "Modern physics," writes M. Markov, "offers an entirely new way to interpret the meaning of 'consists of…'. The universe as a whole may turn out to be a

> microscopic particle. A microscopic particle may contain an entire universe. An elementary particle may consist of an enormous number of particles — indeed, of all types of particles. In such a concept, there is no primordial matter, and the hierarchy of infinitely diverse forms of matter seems to close upon itself."

Markov's hypothesis vividly supports the idea of the eminent Soviet scientist S. Vavilov, who suggested that if the properties of an elementary particle explain much about the behaviour of the universe as a whole, then, by the general principles of dialectics, we are justified in expecting that the properties of elementary particles themselves are determined by the properties of the universe.

> "Could it be," writes Professor Ya. Smorodinsky, "that the same forces operating in the deepest levels of the microworld also shape the structure of the universe? The evolution of the universe, for instance, is linked to nuclear reactions, and its curvature may be determined by neutrino flows. The interconnections in the world of elementary particles are difficult to grasp. But there is growing confidence that no particle in this world is superfluous — that, ultimately, the magnitude of the electron charge is somehow linked to the gravitational constant that governs the motions of cosmic bodies, and that the strange behaviour of kaons is, in some yet unknown way, connected to the birth of galaxies.
>
> Thus, the beginning of the book of nature intertwines with its end. And nothing in it is without purpose."

Translator’s Postface

Particle physics has come a long way from the time — fifty years — this book was was written. International collaborations with several hundred scientists working on large scale projects such as the *Large Hadron Collider* is the norm of the day. Two major breakthroughs that we have achieved and have deepened our understanding of the nature of universe, completing a part of the giant jigsaw puzzle that the universe is, are the discovery of the top-quark and that of the Higg’s boson. Also, the nature and amount of data is such that use of high-speed computers has become mandatory in particle physics research. In this last section, I discuss some aspects of the trends.

Since the 1980s, particle physics has made remarkable strides in understanding the universe’s fundamental building blocks. One of the most iconic breakthroughs was the discovery of the Higgs boson in 2012 at CERN’s *Large Hadron Collider* (LHC), a particle that explains how other particles acquire mass, completing the Standard Model

of physics. Earlier, Fermilab scientists discovered the top quark in 1995, an elusive particle as heavy as a gold atom but minuscule in size. These discoveries were possible thanks to advanced particle accelerators like the *Tevatron* and LHC, which recreate conditions similar to those just after the Big Bang.

High-speed computing has revolutionised particle physics research by enabling scientists to process enormous amounts of data generated during experiments. The LHC alone produces 40 million collisions per second, creating vast data-sets that require sophisticated computational techniques to analyse. Machine learning has emerged as a game-changer, allowing researchers to sift through collision patterns rapidly and identify rare phenomena, such as hints of dark matter or top quarks. For example, new AI-driven systems have accelerated data processing speeds by up to 175 times compared to traditional methods, ensuring scientists can keep pace with increasingly complex experiments. Additionally, quantum computing is being explored as a future tool to tackle even more intricate challenges in theoretical and experimental physics. These advances highlight how cutting-edge technology is intertwined with humanity's quest to unravel the universe's deepest mysteries.

Big data[17] has become a cornerstone of modern particle physics, with experiments like those at CERN's Large Hadron Collider (LHC) producing staggering amounts of information. For example, the LHC generates up to 40 terabytes of data per second during collisions, which must be

[17] Big data refers to extremely large and complex data-sets that exceed the capabilities of traditional data processing software. It is characterised by high volume, variety, and velocity, often requiring specialised tools and techniques for storage, management, and analysis.

reduced to manageable levels using advanced trigger systems and automated selection processes. These systems ensure only the most meaningful events—such as rare particle interactions—are retained for further analysis. Even after this reduction, the annual output can reach exabyte levels, equivalent to millions of home computers' storage capacity. This immense data volume poses challenges in storage, retrieval, and analysis, requiring physicists to develop cutting-edge software and algorithms to efficiently process it. Techniques like machine learning, multivariate analysis, and even quantum computing are being explored to handle this deluge of data and extract insights into phenomena like dark matter or extra dimensions.

Moreover, new tools like the Pandemonium clustering system have been introduced to simplify complex datasets and parameter spaces. These innovations help researchers visualise multidimensional data and prioritise future experiments by identifying areas where improved measurements could resolve theoretical tensions, such as those seen in the B-anomaly problem. Such advancements not only enhance scientific discovery but also reduce computational costs and environmental impact.

Particle physics and cosmology have become deeply intertwined, with discoveries in each field reshaping our understanding of the universe's origins and evolution. One of the most significant impacts of particle physics on cosmology is the development of inflation theory, proposed by Alan Guth in the 1980s. This theory suggests that the universe underwent exponential expansion in its first tril-

lionth of a second, driven by a scalar field in a metastable 'false vacuum' state. During this inflationary period, tiny quantum fluctuations in energy density were stretched to cosmic scales, eventually forming the galaxies and clusters observed today. These fluctuations strongly support inflationary models rooted in particle physics and are consistent with observations of the Cosmic Microwave Background (CMB). The end of inflation led to a "reheating" phase, where the inflationary field's energy was converted into a hot plasma of particles, setting the stage for the Big Bang.

Conversely, cosmology has significantly influenced particle physics by highlighting the existence of dark matter and dark energy, which together make up about 95% of the universe's total energy density but remain unexplained by the Standard Model. This gap drives physicists to search for new particles, such as axions or weakly interacting massive particles (WIMPs), that could account for these mysterious components. Additionally, cosmological observations provide constraints that influence theories involving grand unification or super-symmetry. The extreme conditions of the early universe also serve as a laboratory for testing particle interactions, suggesting mechanisms for baryogenesis that require physics beyond the Standard Model, as current collider experiments have yet to confirm them.

Together, these fields create a feedback loop: particle physics provides mechanisms for cosmic evolution, while cosmology uncovers phenomena that demand new particle theories. This synergy continues to unravel myster-

ies such as dark matter and the universe's first moments, showcasing how advancements in one area can lead to breakthroughs in another.

Of course this is a very brief summary of the state of particle physics, a new volume should be written to cover the topics that I have mentioned in passing here.

I hope that this translation provides justice to the original work and inspires many generations of future scientists.

Damitr Mazanav
Gudi Padwa, 2025